Instruments

THE MAGAZINE OF Measurement and Control

Vol. XIII
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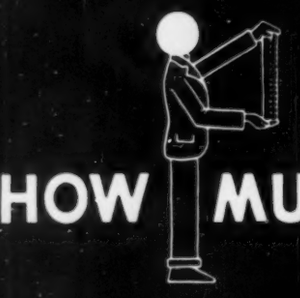
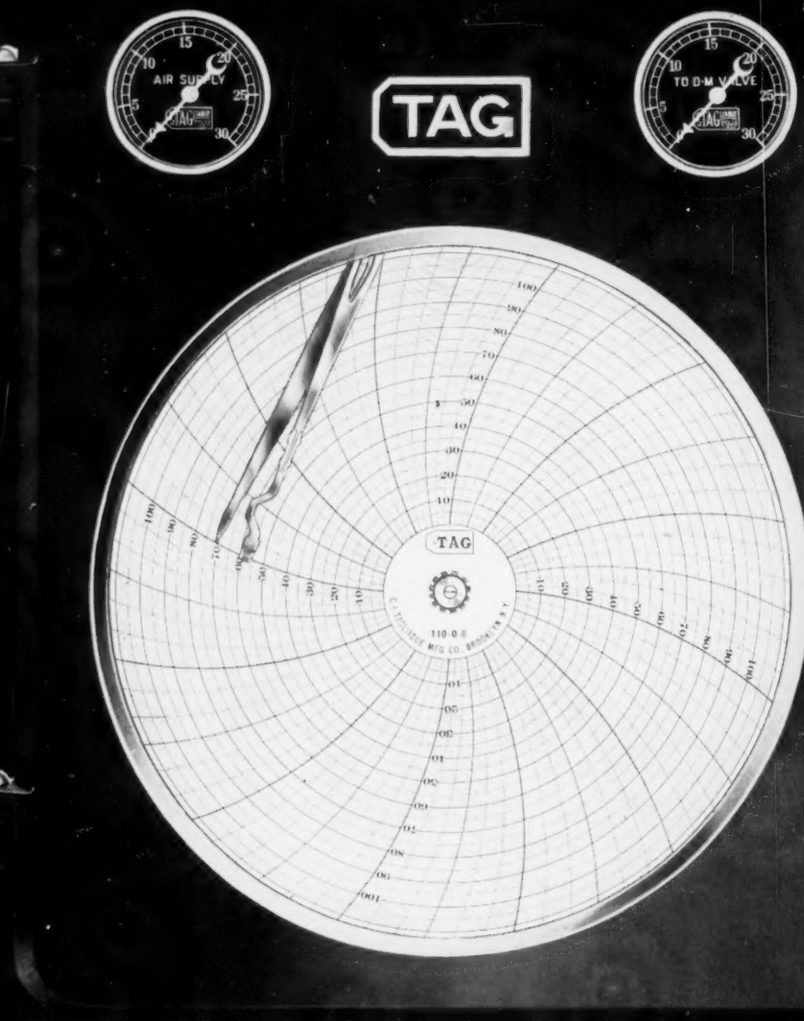
No. 11





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TAG RECORDERS supplement the performance of indicating thermometers or pressure gages with written records you need for reference.

It is not enough that temperature changes and pressure losses may be apparent when the conventional thermometer or pressure gage is looked at . . . Here are instruments that give you a continuous written record of not alone the magnitude of the temperature or pressure change, but WHEN these changes took place — HOW LONG conditions were upset—and precisely HOW MUCH.

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Write for descriptive Catalog No. 1060-I which tells you the whole story.

C. J. TAGLIABUE MFG. CO.

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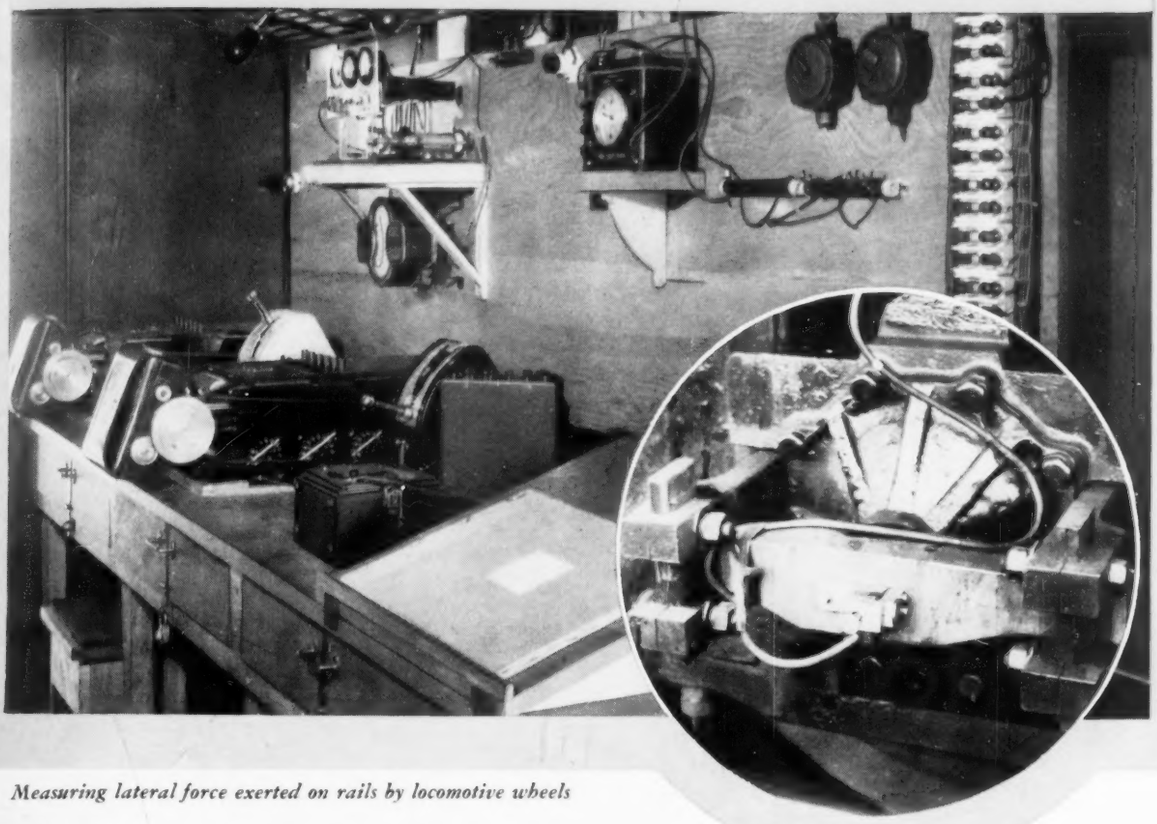
To Measure—STRAIN ELECTRICALLY



Measuring lateral force exerted on rails by locomotive wheels

HOW much would you guess that a concrete road yields to the pounding of a passing truck—or the trifling weight of a boy on a bicycle? How great are the stresses set up in an airplane when it pulls out of a power dive? How much lateral force do locomotive wheels exert on the rails at 20 miles an hour; at 120 miles an hour?

Tough questions, aren't they?—but the strain gage answers all of them and many more.

This G-E instrument measures strain in all kinds of structures. It will indicate how much you can bend a steel bar, 2 inches square, with your fingers—about 1/1,000,000 inch. Yet it's so sturdy that it will retain calibration when mounted on the running gear of a speeding locomotive.

The strain gage is enabling engineers to study the behavior of bridges under higher speeds and heavier loads. Knowledge gained from studies with the strain gage helps in building better roads, lighter yet stronger airplanes, safer storage tanks, and in many other ways contributes to the progress and efficiency of industry.

Strain is but one of the many nonelectrical quantities that can now be measured electrically with G-E instruments. Sound, vibration, light, balance, dimensions—even the infinite shades of color—all yield their secrets to G-E instruments.

For electric measurement, there are accurate instruments that measure current, voltage, resistance, watts, frequency, power-factor—in dozens of styles, indicating and recording, and in ratings to fill every need.

For almost 50 years General Electric has been a leader in the design and manufacture of electric instruments. Its engineers bring to measurement the experience gained in every field of electrical endeavor.

When you have a problem that involves measurement, let us help you solve it. General Electric, Schenectady, N. Y.

HEADQUARTERS FOR ELECTRICAL MEASUREMENT

GENERAL ELECTRIC

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With the speed of the wind!

Thirty-five stories above Chicago's Michigan Boulevard, atop famed Tribune Tower, sensitive wind measuring instruments (Bendix-built) respond to gale or zephyr. In the lobby, 456 feet below, one may read the precise current velocity and direction of the wind and an anemographic record of all its recent vagaries.

Via BENDIX-CORY

AUTOSYN

Remote Signaling Units

A pair of Bendix-Cory Autosyns do the trick, wired in simple circuit (see diagram) between each instrument and its remotely-located dial. They aren't costly. They aren't delicate. They aren't complicated.

Autosyns will transmit almost any kind of reading—pressure, current load, r.p.m., position, rate-of-flow, count, dimension, liquid level. In large aircraft they bring the functioning of engines and control elements under the eye of the pilot. In industrial plants they bring required dial readings to any central point.

Made in several sizes and types, accurate within 1° + or — (½° + or — on special order). Write for details. (It will be helpful if you give some data as to your special problems.)

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MARINE DIVISION
754 Lexington Ave.
Brooklyn, N. Y.

Instruments
THE MAGAZINE OF MEASUREMENT and CONTROL

Vol. XIII NOVEMBER 1940 No. 11

FRONT COVER: Metallurgical chemist checking pouring temperature of an alloy steel melt at Rouge Plant.
Courtesy Ford Motor Co.

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Instruments

THE MAGAZINE OF Measurement and Control

M. F. BEHAR, Editor

Coöperation

IT has been noticed, no doubt, that announcements of meetings to be held by societies devoted to instrumentation are given space in this magazine. The Instrument Publishing Company is delighted to render this little service. Needless to say, there is no charge.

No, that's not quite right. We should not have written "Needless to say." For the benefit of several groups it is necessary to state definitely that our columns are at their disposal. Somehow or other, the impression prevails in certain localities, and among certain groups of measurement-minded men, that "those people in Pittsburgh"—meaning the Instruments Publishing Company—"are in business. They naturally wouldn't do anything for nothing and so there's no use trying to get them to carry our announcements."

That impression is wrong.

Because our publishing company is a business firm, and *because* it believes in building for the future, its policy is to encourage the formation and growth of local groups of men who share a common desire to know more about Instrumentation. This Company—*as* a publishing company—finds it a good business policy to create good-will among all devotees of instrumentation whether or not they they are "prospects" in any way, shape or form. There is a sharp line of demarcation between selling space in advertising columns to manufacturers and dealers who invest in that space in order to boost their sales, and assigning whatever space is needed for announcing or reporting the activities of groups which are non-commercial.

The same applies to announcements of courses in instrumentation. We are eager to run the announcements of such courses, without charge—even when such courses are not given free of charge, and for exactly the same reason that we like to give space to the activities of instrument men's organizations. These groups have to charge dues in order to thrive as clubs or associations or societies or what not. Educational institutions, likewise, except in rare cases of WPA education projects and other assistance, have to charge registration and tuition fees. So long as they are non-commercial, we shall be delighted to aid them in every way that lies within our power.

And this offer of assistance is hereby extended to all "movements" or activities of any sort which aid in promoting the growth of instrumentation—particularly in those cases where the aim is distinctly related to National Defense.

Therefore we extend the hospitality of our columns to all government agencies which have to do with the recruitment or training of instrument men—whether directly or indirectly.

So much for us. What about you? And by you we mean Uncle Sam, we mean state governments, we

American Society for Measurement and Control

Open Meeting—Monday, November 25

Bureau of Mines Auditorium, 4800 Forbes Street, 8:00 p. m.

HIGH SPEED PHOTOGRAPHY AS AN INDUSTRIAL INSTRUMENT

By EARL C. RIEGER,
International Harvester Co.
(Chairman, Chicago Society for Measurement and Control)

Mr. Rieger will show motion pictures taken at the rate of 2,000 frames per second: combustion pictures taken through a quartz window in an engine, valve spring bounce, mechanism movements, etc.

This being an open meeting, visitors will be welcome.

Ample parking space in rear of the Bureau of Mines Building.

Chicago Society for Measurement and Control

Open Meeting—Monday, December 16

OBTAINING ACCURACY IN TEMPERATURE MEASUREMENTS

By: Major M. F. Behar
Editor of *Instruments*

Central Y.M.C.A. Auditorium, 19 So. LaSalle St., Chicago, Illinois.—Dinner at 6:30—$1.25. This is an open meeting and all are invited. If you cannot come to the dinner, come for the meeting and discussion at 7:30.

Please 'phone dinner reservations to Carl Hope at Canal 4100, or address the Society at 2626 W. 31st Boulevard.

mean local governments, we mean unofficial groups, we mean educational institutions, we mean Chambers of Commerce, and every other official or unofficial agency which may benefit through the publication of its announcements in our columns.

In every such agency or unofficial association there should be someone whose DUTY it is to send us notices.*

Another false impression is that this Company "runs" the existing groups of instrument men—or that it means to "run" movements of any sort whatever which are designed to promote instrumentation. Anyone who has "been around" knows that artificially-stimulated organizations do not last long. It is a rigid policy of the Instruments Publishing Company to aid and assist movements and activities which *sprang up by reason of existing demand*—never to give birth to such movements . . . Except, of course, indirectly by preaching the need.

Consider for example what is being called the parent organization of instrumenticians, namely, the American Society for Measurement and Control. We told the story once, but memories are short, so it behooves us to tell it again.

In January 1939 a group of about thirty instrument men, averaging about twenty-five years of age, met spontaneously and formed themselves into an association known as the "American Society of Instrument Engineers." We were not there. This Company had nothing to do with this launching of the first group of its kind. In fact it was not until six months later that the president of that society notified someone connected with the Instruments Publishing Company that such a society was in existence. The notification took the form of a brief letter to your editor, inviting him to attend a meeting of the "American Society of Instrument Engineers." It was only during the next few months that these fine young enthusiasts decided—again of their own volition—to enlist the services of several older engineers. They did not have to ask twice. They had to insist, however, that someone connected with *this* company accept an office.

One of the first things the older men did, for example, was to advise the dominant young element to change the name of their society—to drop the word "Engineers" from its name — to recognize openly that the society is not a professional engineering society—to be proud that it has for its chief purpose to raise the status of its members by creating opportunities for its members to raise their status through their own efforts. The name was changed to American Society for Measurement and Control. Membership is open to non-engineers.

President Pigott, who is prominent in the A.S.M.E., believes that the younger men can *become* eligible for membership in that great engineering society as a direct result of the educational work of the A.S.M.&C. Some of the "seniors" have not only given of their time to committee work, but have prepared and delivered lectures and talks, thereby helping members to help themselves.

There has begun an interchange of lecturers and informal speakers among the various local groups, in direct consequence of the committee work and other society work performed by the seniors for the benefit of the young men who constitute the majority of members in all local groups.

If this company is "running" instrumentation societies or instrumentation courses or instrumentation activities of any sort, the record shows that it is not doing it for business reasons except as it may be casting bread upon the waters. The record shows that both the president of this company and the writer, in the course of their work for local instrument men's groups, have induced several to apply for membership in existing societies of engineers, of chemists, etc.; to subscribe to various scientific and technical journals; to enroll in courses given by educational institutions; to buy technical books published by nearly every technical publishing company in the United States. . . .

And yet there are those who hesitate to send us notices for fear that some subscription salesman would camp on their doorstep!

We never have asked any one of the original group of thirty young men here in Pittsburgh why they waited six months before giving us a hint that they were in existence. It would not astonish us to learn that there was the natural constraint which any non-commercial organization feels toward a business firm — particularly an organization of young men. When the writer was half his present age, he belonged to a chapter which had received a "proposition" greatly to its advantage—and deliberated nearly three months before establishing contact with the business concern in question.

But for older men, such as government officials, engineering professors, and others who need publicity in our columns, to refrain from sending us notices or otherwise calling upon us for assistance —that is absolutely inexcusable.

Moreover—and finally—we are willing to give the benefit of the doubt. This final assertion is made for the benefit of punctilious men (like one we know) who thought that their organizations, being dues-charging organizations, were not entitled to free space in the columns of a publication which they do not support in a tangible way.

Appoint someone to keep us informed. We are not mind-readers. We can't coöperate if you don't.

*Mimeographed notices should be accompanied by letters to the Publisher because this office—like all magazine offices—receives thousands of publicity handouts from hundreds of organizations.

Uncle Sam...

PREPARED TO PRODUCE

WITH TAYLOR'S HELP

FACTORIES hum from coast to coast. Plant lights shine out all through the night. Sounds and sights of this nation preparing to protect our peace, our freedom, our good American way of life.

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That's where Taylor comes in. Taylor Instruments are helping Industry speed up *safe* production. Taylor Instruments are helping Industry produce to more rigid specifications easily, fully, and economically.

Modern plants use Taylor Instruments—like the great new Taylor Fulscope Controller (the unique five-in-one controller!)—to help make plant operations—manufacturing, processing, or whatever they may be—*automatically* exact, *automatically* foolproof, *automatically* faster and more efficient.

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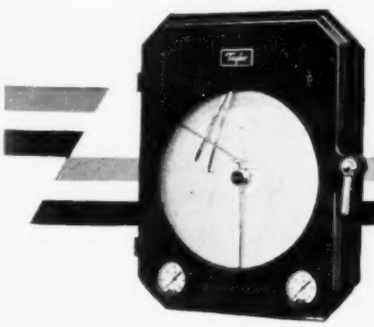
Taylor Instrument Companies, Rochester, N. Y. Plant also in Toronto, Canada.



The new Taylor Fulscope Controller helping Industry's huge preparedness program

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MICHIGAN CITY, INDIANA, U.S.A.

IMPROVED "SPOTLIGHTS"

Rubicon MULTIPLE REFLECTION galvanometers have recently been much improved through redesign of optical system. The definition of the line-image is now so sharp that readings can be estimated to .1 of a millimeter division.

These sturdy self-contained galvanometers are available with sensitivities as high as 5×10^{-10} ampere and 1×10^{-6} volt per millimeter division.

ASK FOR BULLETIN 320

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Electrical Instrument Makers
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Galvanometers, Electrometers, Potentiometers, Colorimeters, Wheatstone & Kelvin Bridges, Resistance Standards, Resistance Boxes, Coil Testers, Clip-on Ammeters, etc.

THE MONTH'S NEW INSTRUMENTS

In this department we strive to report each month ALL the new devices for measurement, inspection, testing, metering and automatic control.

When writing to manufacturers directly, please mention this department as your source of information. Or write to Information Section, Instruments Publishing Company.

Speed Indicator for Timing Aircraft Catapults

A new speed indicator designed to eliminate much of the hazard in catapulting airplanes from ships may, with some changes, be used to time other moving objects. The device includes two coils mounted one foot apart in the catapult at the end of the run and an alnico permanent magnet to be mounted in a skid on the catapult. The

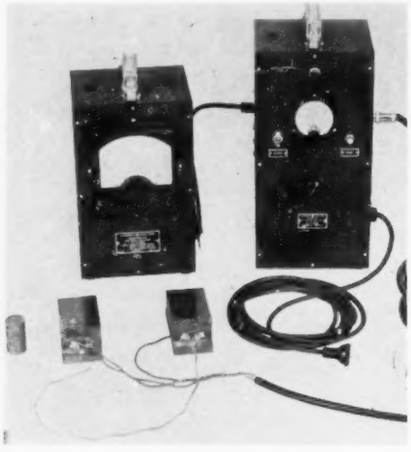


Fig. 1

skid is shot down the catapult with or without a plane on it. As the magnet passes over the coils, voltage impulses are set up in them and the speed of the skid is registered on a connected instrument, the needle

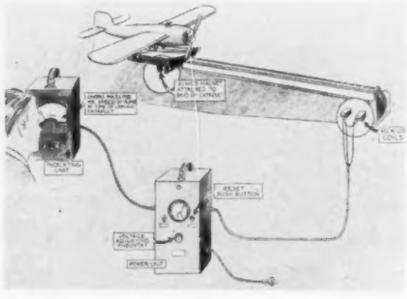


Fig. 2

of which remains deflected until a button is pushed. With the device it is possible to check the adjustment of a catapult by shooting the skid down the track without risking a pilot and plane. If the skid registers the proper speed, the plane can then be placed on the skid and shot off with the correct adjustment of the compressed air mechanism driving the catapult. The speed indicator actually measures the time interval between the voltage impulses from the pick-up coils. Thus any short time intervals which can be co-ordinated with impulses of this type can be measured. In timing planes leaving catapults at around 60 miles an hour, the device has an accuracy of $\pm 2\%$. *—General Electric Co., Schenectady, N. Y.*

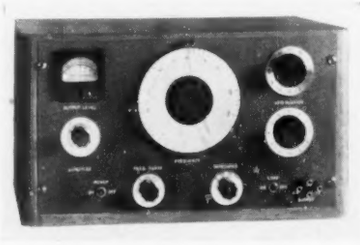
Temperature Controller

New remote-bulb thermostat for proportioning control is designed for applications where the requirements call for a motor-operated valve or damper to be positioned

"in accordance with the load variations." Remote bulb and bellows assembly are hydraulically formed. Thermostats for 2-position control (with snap acting contacts) and for floating control, are also available. *—Barber-Colman Co., Rockford, Ill.*

Audio Signal Generators

The audio signal generators are designed for time saving performance. The various features have been selected with the aim to make these instruments suitable for accu-



rate and rapid measurement work. They are for general laboratory applications supplying known voltage as well as a known frequency at the commonly used impedance levels. They are particularly suitable for gain measurements because no auxiliary apparatus is required, and provide an excellent source of voltage for distortion measurements because their waveform distortion is very small. The Model 205-A consists of a resistance tuned oscillator in combination with an output meter, attenuator, and an impedance matching system. The Model 205-AG includes input meter for gain measurements.—*Hewlett-Packard Company, 481 Page Mill Rd., Palo Alto, Calif.*

Individualized to meet your specific instrument design specifications.

Clare Relays are available in innumerable coil, contact, adjustment and timing combinations — accurately made of quality material.

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Gives Positive Protection to the Wire against Corrosion, Acids, Oils, etc. ★ Pliable, Compact, Light in Weight and Protects Mechanically like Armor. ★ Produces added Stiffness yet can be Bent to shortest Radii. ★ Outside Diameter can be held to close Tolerances and any required wall thickness can be made.

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Specialists in Accurately drawn Seamless ALUMINUM, COPPER and BRASS Tubing in the Smaller Sizes.
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Distortion Analyzer

The distortion analyzer consists of two band elimination filters, one for measurements at 400 cycles and one for measurements at 5,000 cycles, and a calibrated at-

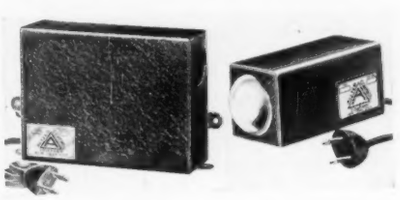
tenuator. With the voltage to be analyzed adjusted to the proper frequency the fundamental is eliminated completely. The residual voltage containing the harmonics can then be observed with an oscilloscope or measured with a sensitive meter. When the frequency has been adjusted so the fundamental is eliminated, the elimination filter is switched out and a calibrated attenuator is introduced. Then the attenuation of the fundamental is increased until the fundamental voltage has the same magnitude as the residual harmonics alone. Further comparison can be made by changing the switch back and forth.—*Hewlett-Packard Co., 481 Page Mill Rd., Palo Alto, Calif.*

Photoelectric Colorimeters

A series of photoelectric turbidimeters and colorimeters is announced, comprising four distinct models, each modifiable, permitting more than twelve different set-ups. Two models have an external galvanometer of the self-contained lamp-and-scale type. Another has mirror-scale type Weston external galvanometer. Others have built-in galvanometers which are likewise of anti-parallax design. These are completely self-contained and portable. All are regularly supplied for operation on 110-120-volt 60-cycle a.c., but can be supplied in a.c.-d.c. models, also for other a.c. voltages and frequencies. In all models the quantitative determination is based on the use of two photocells in a balanced circuit, thus achieving independence of line voltage, cell sensitivity, etc. Special attention is said to have been given to elimination of thermal effects and compensation for other common sources of errors. Optical design is such that only one filter of each type need be used. *Sample holders, Filters, etc.:* Announcement lists a complete assortment of general-purpose types and a wide variety of special-purpose types.—*Luxtrol Co., 54 W. 21st St., New York City.*

Photo-relay Units

Photo-amplifier relay units, in three models, for use on a.c. and d.c. has been developed for the following uses: alarms, opening and closing doors, turning lights on or off;



to operate bells, chimes, horns, buzzers, or various types of signals; to start motors, close valves, or run safety devices. Other applications are in counting, regulating, sorting, and smoke control. Type PR1 relay is for use where relatively large amounts of light are available; type PR2 (illustrated at left) for relatively small amounts of light and type PR3 for applications where it is either impossible or undesirable to use a separate light source. The light source is illustrated at the right.—*Allied Control Co., Inc., 227 Fulton St., New York, N. Y.*

A 24-HOUR RECORD—giving accurate and dependable measurements so vital to efficient and economical operation.

Hays Combustion Meters employ the Orsat principle for measurement of CO_2. Water operated — no moving parts—extreme accuracy coupled with dependable performance.

There is a Hays Combustion Meter to fit every requirement—remote or integral mounting, indicating or recording or both. Write to 925 Eighth Avenue, Michigan City, Indiana, for free catalog.

The HAYS CORPORATION
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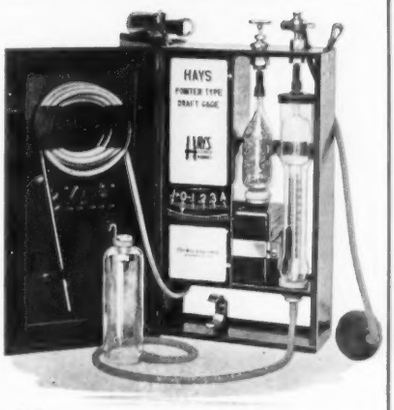
MICHIGAN CITY, INDIANA, U.S.A.

A LABORATORY JOB DONE IN THE FIELD



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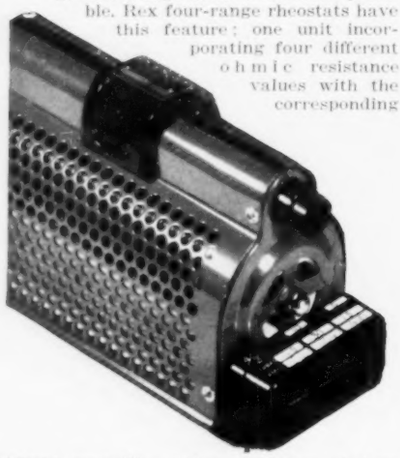
Four-Range Rheostats

The multiplicity of applications in plants and laboratories makes the use of regulating devices desirable which similar to multi-range measuring instruments provide a greater range than heretofore possible. Rex four-range rheostats have this feature: one unit incorporating four different ohmic resistance values with the corresponding



current capacities, takes the place of four different rheostats. The Rex four-range rheostat has two closely bifilar wound windings, so that each turn of one winding runs alongside the turns of the other winding. Both windings—operated by one slider—are of two wires of identical diameter made of material having different specific ohmic resistance, such as a nickel-copper and a nickel-chrome alloy. Therefore the resistance value of both windings is different. The resistance material is insulated with Fiberglas, which retains satisfactory dielectric strength at the temperature reached when the rheostat is fully loaded. — *Rex Rheostat Co., 37 W. 20th St., New York, N. Y.*

Tube Tester

Like all Hickok tube testers this instrument tests tubes by measuring dynamic mutual conductance in micromhos. It is designed primarily to assist dealers in making

more tube sales as it has a large 9" square meter with illuminated dial that clearly indicates good—bad—doubtful for each tube so that there can be no doubt in the customer's mind. Readings are also given in micromhos. The Model 530-M tests all tubes including ballast tubes, magic eye tubes, miniature tubes, etc. It tests for shorts—hot or cold. Contains a sensitive noise test and detects radio frequency noise. Has an accurate, sensitive gas test.—*Hickok Electrical Instrument Co., 10529 Dupont Ave., Cleveland, Ohio.*

★ Moisture Teller ★

Rapid and accurate moisture test in percentage by drying. Drying temperature controlled by thermostat. Ideal for plant moisture control or laboratory moisture determinations.

Time required to dry the majority of materials is one minute.

Suitable for granular—fibrous—crystaline materials in industries such as:

Sand—Textile—Tobacco
Ceramic—Rubber—Food
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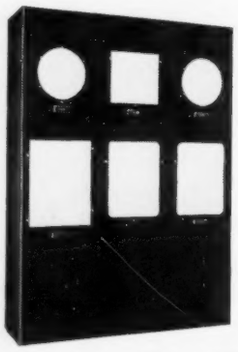
FALSTROM



STEEL PANELS

FALSTROM Precisioned Steel Panels are specified by engineers for their Strong Construction . . . Adaptability . . . Fine Appearance . . . for use in—

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OIL REFINERIES
PUBLIC UTILITIES
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FALSTROM COMPANY of PASSAIC N.J.

Program Clocks

Two new synchronous program clocks operating time signals: Type P512 will operate a signal at any five-minute period and Type PD124 will operate a signal at any one-minute period. These clocks have a large, legible 24-hour dial cam. Pointers, connected to a contact arm, ride the dials and permit the contact arm to fall only when preset time is reached. These units are operated by heavy duty synchronous motors, and contact arrangements are such that accuracy is assured. Contact can be so arranged as to

operate a signal either in one ring or a coded ring, or for a definite duration of time, from 2 to 6 seconds. Units are compact and enclosed in dust-proof case. These clocks can be built to operate for many different purposes such as daily siren testing, timing industrial processes, and signaling the start and end operating periods.—*Zenith Electric Co., 845 S. Wabash Ave., Chicago, Ill.*

Electronic Level Control

Electronic level control Type P30 makes available a simple electronic relay for level control of both conductive and non-conductive fluids and powders. Equipment is avail-

able to meet all specifications including single level control, on and off control at two levels, boiler feedwater control, and tank condensate signals. Installation merely entails attaching a probe fitting to the surface of the tank. The equipment includes no mechanical parts.

For two-level control probe fittings or electrodes are attached to the tank at levels representing the low point where pumping starts and the high level where pumping stops. These probes are wired to the control. When the liquid level falls below the lower probe, the circuit closes which starts the pump, and the tank fills. When the level rises to the upper probe, the fluid itself acts as a conductor of the small amount of current required for the operation of the level control. This opens the pump control circuit.

Type P30 can be used with combustibles, and is recommended in connection with all conductive fluids as well as such insulators as: resin, rubber, latex, paraffin, mica, glass, cement, linseed oil, shellac, mineral oil, wax, waterglass, lacquer, and thinner. Special tank fittings are available for use in corrosive liquids.—*Photoswitch, Inc., 21 Chestnut St., Cambridge, Mass.*

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(A trade name)

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The most complete equipment ever offered for studying Diesel and gasoline engine pressures, torsional, linear, and planar vibrations.

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PLANAR VIBRATION PICKUP UNITS

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DISPLACEMENT METERS (Torsional and Linear)

TYPE II VIBRATION OUTPUT INTEGRATORS

CEL Type VI Air Flow Indicators, Single and Multiple Stage Fuel Flow Indicators, Single and Multiple Direct Pressure Engine Indicators, Magnetic Wall Thickness Gages, and other Special Laboratory Instruments are internationally used.

●

COMMERCIAL ENGINEERING LABORATORIES

Manufacturers of

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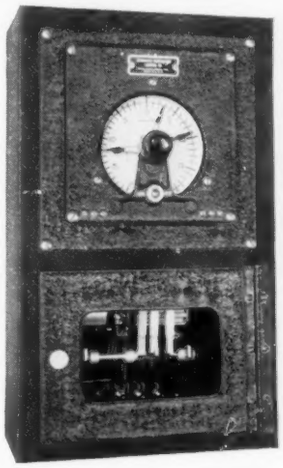
4612 Woodward Ave. Detroit, Mich.

Sequence Timer

The timer illustrated is widely used when it is desirable to have, in one instrument, the means of controlling the sequence and duration of all essential actions in a firing



program. With this timer the firing at each end of the furnace is subject to individual adjustment by the turning of an external knob. Elapsed firing time is indicated by the progress of one hand on the visible dial. Individual actions, such as the operation of valves and dampers are governed by cams which are readily adjusted to the exactly desired time for actuation and duration.—*Automatic Temperature Control Co., Inc., 34 E. Logan St., Philadelphia, Pa.*

Piston Ring Wall Pressure Tester

The Link Piston Ring Checker is designed to show the load required to compress a piston ring to true cylinder bore diameter. Yokes are fitted to the weighing-table and compression head respectively of the tester. In raceways on the inner circumference there are a series of floating cages on rollers. Each cage carries a pair of removable radial pins, as shown in the illustration. Cover plates for the yokes have been removed in the photograph to reveal the construction. As the yokes are brought together the radial pins close the piston ring to a true circle of bore diameter and the load required is read on the dial. The movement necessary to secure a true circle is pre-determined by use of a master ring-gage, and an electrical signal circuit indicates exactly when that point is reached. The load is then read on the load-dial below. Closely adjustable mechanical stops at each side prevent overtravel and deformation of rings. It is obvious that a set of radial pins and a master ring-gage are required for each ring size. The yoke assembly itself will accommodate a broad range of diameters. Standard testers are available in two ranges one with 12 pin assembly, covers the range from 2¾" to 4", while the second, with 16 pin assembly covers diameters from 3¾" to 5½". Testers for larger sizes of rings are available on special quotation. Either of the two standard range testers may be had with 0-50 lb. or 0-250 lb. load units.—*Link Eng. & Mfg. Co., 1054 W. Baltimore Ave., Detroit, Mich.*

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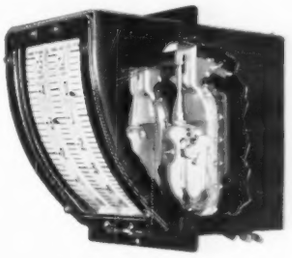
METERS and CONTROL *for Boiler Room Service . . .*

Boiler Meters Reduce fuel costs, lessen maintenance and outage, lower standby costs, and add capacity. They indicate, record and integrate Steam Flow from the boiler, record Air Flow supplied for combustion and record Flue Gas Temperature.

Bailey Boiler Meter

Multi-Pointer Gages for indicating drafts, pressures, differentials are available with any number of pointers from one to twelve. They are actuated by sturdy yet sensitive diaphragm units.



Multi-Pointer Gage

Flow Meters. For indicating, recording and integrating the flow of steam, feed water, compressed air and other fluids.

Coal Meter

Granular Material Meters For accurately measuring the flow of coal or other granular materials in gravity chutes from overhead bunkers. The total quantity of granular material is shown on a large illuminated counter which may be easily read at a distance of 50 feet.

Control Systems Make possible the everyday operation of equipment for steam generation and utilization at test efficiencies. They are applied to the control of combustion, feed water, superheat, desuperheat and other factors.

Complete Information on any of the above Bailey products will be gladly furnished upon request.

G-14

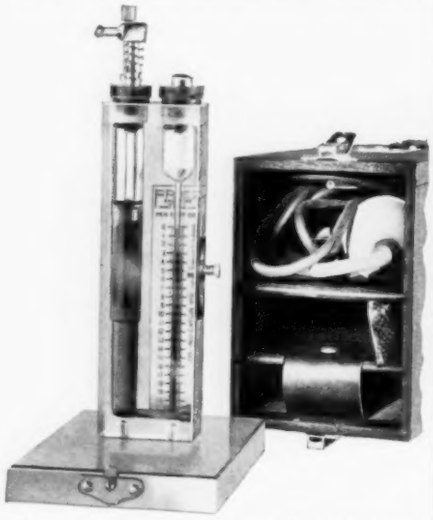
BAILEY METER • COMPANY •

1041 Ivanhoe Rd., Cleveland, Ohio

BAILEY METER COMPANY LTD., MONTREAL

CO_2 Indicator

The new CO_2 indicator is machined from a solid block of crystal-clear plastic, while the metal parts are of stainless steel. The absorbent solution is a brilliant red in color,

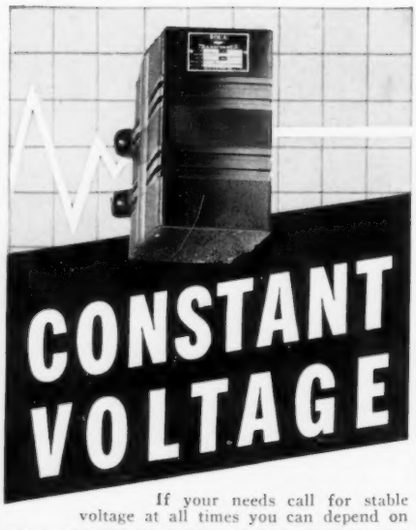


and its level is clearly reflected from the polished scale, allowing the operator to line up the liquid level, its reflection and the scale graduations, thus preventing any possibility of parallax error. Only three simple steps are involved in using the indicator, which is accurate to within ½% CO_2. The indicator is supplied complete with a carrying case, in which space is also provided for a stack thermometer and a full-size draft gauge.—*Julien P. Friez & Sons, Baltimore St. & Central Ave., Baltimore, Md.*

Power Rheostat

Extreme sturdiness, both mechanically and electrically, characterize the new power rheostat, in which selected resistance wire is wound on an insulated aluminum core.

The resistance element is bent round, placed in the slot of the ceramic shell, and firmly imbedded in a cold-setting inorganic cement. This construction provides maximum heat conduction and dissipation from winding to special ceramic casing. No corrosion of the wire is possible, nor any weakening, since no high temperatures are required in setting the cold-setting cement used. A graphited-copper contact shoe rides the brass third-rail ring and the winding, with a positive, velvety sliding contact. The ingenious tripod-type rotor provides for a three-point support on the brass contact ring and the winding, against the concealed helical spring pressure, for the smooth, easy, non-binding rotation. The rotor is insulated from the metal shaft by a center ceramic insulator. The rheostat may be mounted in any position with regard to its terminals and knob rotation, by means of the adjustable locking pin and disc. For the present, only the 25-watt size is available.—*Clarostat Mfg. Co., Inc., 285-7 N. Sixth St., Brooklyn, N. Y.*



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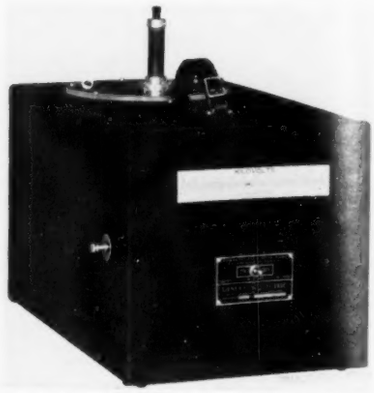
Electrostatic Voltmete

Static electricity in a powder plan can be a very troublesome hazard, so a well-known chemical company recently conducted tests with a G-E electrostatic voltmeter to



find the extent of the static electricity generated on their conveyor belts, motor drive belts, rubber tired trucks, and from actual walking on floors. In checking the V belt of a 25-hp. motor, the 20,000-volt static voltmeter went off scale—observation of the discharge spark indicating the presence of approximately 37,000 volts on the V belt. Another test indicated that 6000 volts were generated simply by walking across the carpet of an office. These preliminary tests led to more extensive checks in all of the chemical company's plants. As a result, belt dressings were investigated to find one of a conducting nature that would permit a continuous discharge of accumulated static electricity. All trucks were equipped with grounding chains, various types of flooring were investigated, and many other changes were made to minimize the hazards of explosion from static electricity. The G-E electrostatic voltmeter used in detecting the static is a 20,000-volt portable instrument designed for both a-c and d-c measurements of voltage on systems where one line is grounded. Operation is simply a matter of grounding the case, energizing the light source, and making the high-voltage connection.—*General Electric Co., Schenectady, N. Y.*

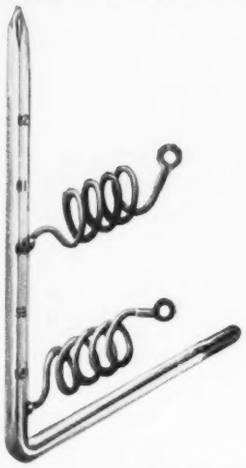
Chronograph

The Multichron, Style No. 230/7B performs four important time-recording duties. There is a dial, divided into fifth-seconds, for *Timer* purposes; also regular every day

hour and minute *Watch* dials; the circles in the center are a *Tachometer* gage to record miles per hour speed; the extreme outer track is a *Telemeter* dial to indicate distance of light and sound. The Multichron is equipped with a 45-minute register. The two-button model affords a time-out feature, working thus: pressure on one button will consecutively start, stop and again start sweep-second hand. Pressure on the other button brings sweephand back to zero. The movement parts are rust-resistant and thoroughly non-magnetic. This Multichron is for use in aviation, in time-study work for industry, in research. It is available with black dial, as shown, or with white dial.—*Jules Racine & Company, 20 W. 47th St., New York, N. Y.*

For Extremely Close Temperature Control

Visual-Stats



● Sensitivity of a hundredth of a degree is easily attainable. ● Top of mercury column visible at control point (where most important) because electrodes terminate at back of tube. No encircling metal bands! ● Available in angle form (illustrated) or conventional straight form. ● Send for brief, attractive bulletin.

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PHOTOELECTRIC COLORIMETER
and
ABRIDGED SPECTROPHOTOMETER

A light measuring instrument of great versatility for all research and routine tests involving

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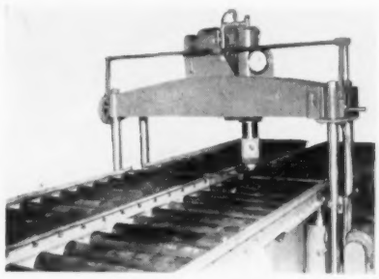
Wide Plate Brinell

A Brinell machine for testing wide plate at any point without removal from the conveyor, consists of a flat base and cross-rail assembly supported by four posts. The test



cylinder is mounted on a carriage sliding between the rails and is moved across the plate by a small motor operated by push button control. The conveyor section runs between the posts and that the test-ram travel is sufficient to contact the work without any adjustment other than movement of the operating lever shown on upper right. A heavy work-support rail runs between the conveyor rollers slightly below flush when idle. When a test is being made this rail is brought into contact with the bottom side of the plate, by small movement of lever shown at lower right, and takes the load. In operation the plate passes over the rollers the desired distance and is held in that position by the work-support rail. Tests are then made across the width. The plate is then released, moved forward and testing operation repeated. — *Detroit Testing Machine Co., 9390 Grinnell Ave., Detroit, Mich.*

Line Voltage Compensator

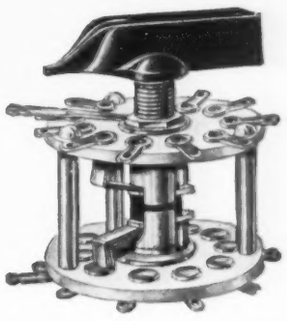
The type "LC" Transtat, a voltage compensator, is a manually operated unit especially designed to permit compensation for small voltage variations in alternating-current circuits. As it functions with equal effectiveness, regardless of changes in power factor, frequency and amount of load, it is well suited for use with all types of electrical equipment in maintaining input voltage constant so as to enable both efficient operation under all conditions and maximum operating life. Voltage may be adjusted smoothly and without circuit interruption to within a fraction of a volt of the desired value.

This new voltage compensator is a continuously adjustable, transformer-type voltage regulator designed to cover only a limited voltage range. It consists of a small, adjustable, auto-transformer-type regulator which is connected across the line and an auxiliary buck-and-boost transformer with its secondary winding connected in series with the line. Voltage regulated either side of a center-tap in the winding of the regulator element is fed to the primary winding of the transformer, thus enabling either a bucking or boosting voltage to be set up in the secondary winding which is in series with the line. Standard types permit full correction over a range of ±10% and are available for service in 115-, 230- and 460-volt, 50- to 60-cycle, circuits. Equipment for single-phase and polyphase service is made in ratings from 2.5 Kva. to 85 Kva. output.—*American Transformer Co., 178 Emmet St., Newark, N. J.*

FOR *Permanent* LOW CONTACT RESISTANCE, *use the*

SHALLCROSS

ROTARY SELECTOR SWITCH

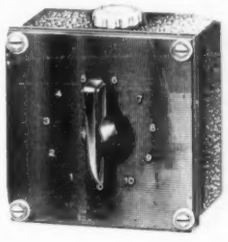


Particularly designed for use with the Thermocouple and other instrument circuits, also to control circuits such as found in high grade electrical apparatus.

Made with a very superior ceramic switch plate known as "steatite", and has *eleven solid "fine" silver contacts and contact arms.* The average contact resistance in this switch is .00075 ohms or less. Supplied with more or fewer contacts, with or without stops, shorting (bridging) or non-shorting.

COST SLIGHTLY MORE—BUT *WORTH MUCH MORE* BECAUSE THEY LAST LONGER, ARE MORE ACCURATE.

Also furnished *enclosed*—mounted on a beveled bakelite panel with etched dial and housed in a cast aluminum box.



These boxes are also available with Shallcross No. 531 Switch, employing brass contacts and phosphorus bronze contact arm.

Write for Switch Bulletin No. 141-HR

SHALLCROSS MFG. CO.
Instruments – Resistors – Switches
COLLINGDALE, PA.

Bore Inspection Telescope

This instrument provides a clear and detailed view, much enlarged, of the inner walls of gun barrels, tubing, pipes, boiler tubes, and many other hitherto inaccessible

FIELD OF BORE INSPECTION TELESCOPE M2123

recesses. Small holes, cracks, pits, scratches and other defects are readily seen. Inspection can be made in tubes 1 to 4 inches in diameter and, by means of extensions to a depth of 20½ feet.

The main unit of the bore inspection telescope permits inspection of tubing to a depth of 4½ feet. It consists of an illuminating head, a telescope tube containing the necessary optics, and a removable eyepiece. Extension tubes, each 4 feet long, and containing the necessary optics, can be added to the main unit to correspondingly increase the depth of inspection. As many as four of these extension tubes can be added, giving a maximum usable depth of 20½ feet. The method of connecting the extensions is such as to ensure a rigig tube.—*Gaertner Scientific Corp., 1201 Wrightwood Ave., Chicago, Ill.*

Radio Set Tester

The Series 954, combination dynamic mutual conductance type tube tester and 37 range super-sensitive AC-DC multi-range set tester is a complete service laboratory in one compact unit. It provides every facility for accurate and reliable solutions of tube test and of measurement problems arising from modern radio (A.M. and F.M.), television, industrial and laboratory practice. 20,000 ohms per volt including ranges of

MEASURE R. P. M.

without even seeing
the rotating element

THE "FRAHM" TACHOMETER

operates merely by being held against or mounted on the machine under test and imposes no load. There are no belts, gears or electrical connections—simply a set of accurately tuned steel reeds which operate by resonance. Various ranges from 900 up to 30,000 r.p.m. Unique also for measuring vibrations per minute.

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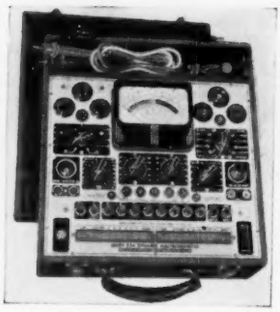
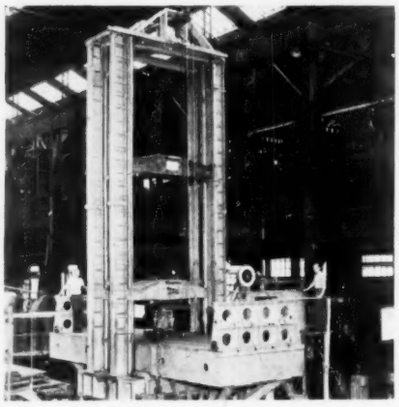


6,000 volts AC-DC; 60 microamps.; 12 amps. and 60 megohms. Available in 4 models, complete with batteries and extra high voltage test leads. — *Precision Apparatus Co., 647 Kent Ave., Brooklyn, N. Y.*

Materials Testing Machine

A 100-ton materials testing machine has the following specifications: 34 feet high, 21 feet wide and 24½ feet from front to back. The transverse table, one of the largest ever built is 8 feet wide.

Not only is the machine one of the largest ever built in the United States, as well as the world, it is also among the most accurate. Though it can exert a maximum of 700,000 lbs. pressure, the mechanism has recorded a maximum error of .06%, making it one of the most sensitive machines of this type ever built. This machine will finally be installed in a large university laboratory in Russia.—*Riehle Testing Machine, America Machine & Metals, Inc., East Moline, Ill.*



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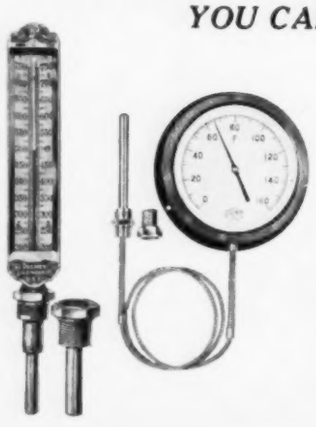
YOU CAN'T GO WRONG . . . WITH THERMOMETERS MADE BY PALMER



Just as Palmer "Red-Reading-Mercury" Indicating Thermometers are known everywhere for sensitive and accurate Temperature readings, just so Palmer's latest products: "Recording" and "Dial" thermometers carry this same high quality and you will be amazed at their accuracy and sensitive reading.

(Send for NEW edition No. 300D catalog)

THE PALMER CO.

Mfr: Indicating-Recording-Dial Thermometers

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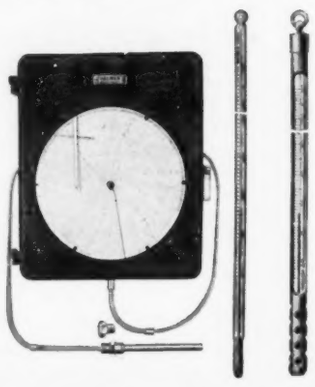
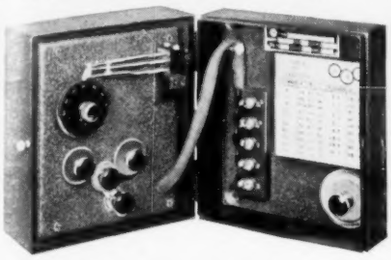
Canadian Plant: King & George Sts., Toronto.



Repeat Cycle Timer

eries 4100 timer (illustrated) will repeat a selected cycle in any total period when current is supplied to the terminals. Adjustment of a split cam offers an infinite choice



of settings for time-contact-held from 0 to 100% of the total cycle. The cam, conveniently located, is easily adjusted, and has the ability to retain the setting when the timer is subjected to vibration. Six ranges for total time are available with standard gear trains as follows: (a) 5 seconds to 80 seconds, (b) 1 minute to 16 minutes, (c) 3 minutes to 48 minutes, (d) 5 minutes to 80 minutes, (e) 1 hour to 16 hours, (f) 3 hours to 48 hours. Nineteen steps of total time are available in each of these standard ranges. Gear changing is accomplished quickly without tools and can ordinarily be completed in a few seconds. Special gears, quickly furnished, offer a great variety of total cycle ranges up to 12 months and more. All gears are cut to provide smooth, reliable operation. —*Automatic Temperature Control Co., 34 E. Logan St., Philadelphia, Pa.*

Gage for Indicating Width of Moving Steel Strip

A new photoelectric gage gives a continuous and accurate indication of variations in the width of moving steel strip without making contact with the metal.

With the new device, the width of the strip can be measured "on the fly" at any point or points in the mill and variations from the required width can be accurately transmitted to any number of desired stations such as the control pulpit, etc. Thus while the strip is moving through the mill, adjustments to the edging rolls can be readily made by the operator to correct deviations from normal width. Although the gage was developed primarily for use on hot-strip mills, it can be readily applied to many other industrial jobs involving width control of moving strips of material. In operation, both edges of the strip are followed simultaneously by narrow light beams and true indication of its width is given regardless of any sidewise movement of the strip. The movements of the light beams are photoelectrically transmitted to indicating instruments.—*General Electric Co., Schenectady, N. Y.*

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MAYBE WE CAN HELP YOU! Many production problems are caused by noise and vibration. We've had long experience with noise detection and control in aircraft, refrigerators, automobiles, motors and many other products. We're specialists in practical acoustic methods and equipment for production testing. If you have a problem of this kind, tell us about it. Why not write us today?

Electrical Research Products Inc.
76 Varick Street, New York, N. Y.
A Subsidiary of
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A midget capacitor motor with built-in speed reducer

Here's a new, small, but rugged built-in spur gear speed reducer motor, designed especially for continuous duty on instruments, timing mechanisms, and various control apparatus requiring exceptional reliability. Available in synchronous or non-synchronous capacitor models, in speeds from one to 300 rpm and torques from 1.3 to 120 inch-ounces. The motor develops from 1/750 to 1/2000 hp, depending upon the type of winding used.

1/1500 Hp Continuous Duty

The Type K motor is not a "toy" motor. It has no "permanent" magnet and no internal switches or brushes. It has distributed windings, a high starting torque, and can withstand stalling indefinitely. The unit is fully enclosed to provide complete protection.

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MOTORS

Bodine Electric Company
2244 W. Ohio St., Chicago

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Company ..... Title .....
Address .....
City ..... State .....

Elementary Theory of Automatic Temperature Control

By C. O. FAIRCHILD
Director of Research, C. J. Tagliabue Mfg. Co., Brooklyn, N. Y.

THE subject of automatic temperature regulation is in great need of elucidation and simplification at the present time, because the many papers and discussions which have appeared in recent years have approached it from angles which leave it obscure to the new student and busy engineer. Some papers have been wholly descriptive and others mathematically abstract. The literature on the subject is apparently voluminous for it is an old field of applied physics which is entered occasionally by engineers and others from many other fields. Often these entrances are followed by the publication of notes describing the device which was invented during the visit. One author recently stated that "little has been published relative to the fundamental principles" and another "the science of the automatic regulation of temperature is at present in the anomalous position of having erected a vast practical edifice on negligible theoretical foundations." The theoretical foundations are so old that they have merged into the landscape and the fundamental principles found in classical texts on the sciences have not sifted into the field in generally recognizable and useful form. The young engineer can learn only with difficulty about the elementary theory from the available descriptive essays and ordinarily inaccessible patent specifications, and, so far as we are aware, no analytical approach to the subject has been published which could be generally useful. Ivanoff's[1] excellent essay in which he used one of Fourier's heat conduction equations in disguised form proved, at least, that too rapid mathematical excursions are apt to lead to erroneous generalities, and the discussion which followed his presentation demonstrated the futility of his method of approach. Since the expression of ideas in mathematical language is the essence of applied science and engineering, it is essential that the principles of this subject be expressed in mathematical form, but it also is essential that mathematical flourishes be avoided.

It is particularly desirable to begin the study of this subject with the simplest mathematical expressions because the theories of heat transfer are more difficult to grasp than, for example, those of flow ordinarily involved in the regulation of the level of a liquid. We shall find it necessary presently to confine our treatment strictly to the regulation of temperature as a problem essentially different from the regulation of anything else, and we are inclined to disagree with those authors who are currently attempting to teach the subject with the use of hydraulic analogies, and who imply that a study of level control is a good approach to that of temperature control. For example, Mason[2] suggests that a study of control of the level of a liquid in the continuous process may be universally applicable in the study of automatic regulation, including temperature, failing to note that the analogy converts to temperature control, not of the continuous, but of the batch process; he also fails to distinguish between the two processes. The conversion results from the substitution of the flow of heat for the flow of a liquid. For a study of the thermal processing of liquids where the heat is transferred principally by convection, there are available theories based on the analogies of fluid flow and heat transfer,[1,2] but it would seem advisable to handle the problems of conduction and radiation in a conventional manner.

The first principles of automatic control are best derived from a study of so-called throttling control, in which the heat supply is maintained at some intermediate value, for example, by a partly open valve. A better name for this method of control would perhaps be corresponding[3] control because for every temperature within the throttling zone of the controller there is a corresponding position of the valve. It seems that in spite of the fact that volumes have been written and hundreds of patents issued on this method of control, there remains unavailable, so far as the writer is aware, any simple exposition of the fundamental concepts which should be identified with it. Most writers are prone to plunge into the general subject with vague expression of the first principles, or omission of reference to them as too elementary to consider, while most inventors pay little attention to the fully-developed theories of heat transfer and damped periodic motion, confining their attention for the most part to the invention of various means for "beating" physical laws.

Probably the *first principle* of control is that the controller combats or corrects for a change in temperature, that is, if the temperature departs from the selected control point, the controller acts to restore it.

The *second principle* depends on the fact that temperature is always controlled indirectly, generally by controlling the rate of supply of heat according to the variations in temperature, thus leaving the load or heat demand an independent variable. Hence, the result of controller action depends not only on the characteristics of the controller, but on those of the plant† being controlled, including independent variations in load.

The *third principle* is (in corresponding control) that a permanent change in demand for heat can be corrected only partly and only with an accompanying permanent change in temperature in the opposite sense. Thus if the demand decreases the temperature remains higher than the selected control point in order that the heat input may be maintained at a lower rate. This departure of the temperature from the control point may be called the "load error." A similar departure may result also from a permanent change in the potential of heat supply, for example, the pressure of fuel gas or the voltage of electric supply, but in this case the error is in the same sense as the change in potential.

While the load error can be kept small by designing this controller so that its corrective action is relatively large, the error will remain real although it may be reduced to a negligible value.

The idea of the characteristic of sensitivity is old, and it has long been recognized that as the throttling zone of a controller is narrowed, that is, for example, a valve is made to move to its limits for a smaller range of variations in temperature, the controller appears to be more sensitive and corrects the better for changes in temperature, to the point where it may be so sensitive that it imposes maintained oscillations upon the plant—it is said to "hunt." It is essential then to be able to define sensitivity with some degree of exactness.

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*Presented before the Symposium on "Temperature, its Measurement and Control in Science and Industry," American Institute of Physics, New York City, Nov. 2-4, 1939.

[1]A. Ivanoff. Theoretical Foundations of the Automatic Regulation of Temperature. *Journal of The Institute of Fuel*, Vol. 7, No. 33, Feb., 1934, pages 117-130. Discussion: pages 130-138.

[2]C. E. Mason. Quantitative Analysis of Process Lags. *Transactions A.S.M.E.*, Vol. 60, No. 4, May 1938, pages 327-334.

†In this article, "plant" signifies what is often called "the application"—the heat processing unit to which the controller is applied. —EDITOR

[3]E. S. Smith, Jr. Analysis of Fluid Rate Control Systems. *Instruments*, Vol. 6, March 1933, pages 54-60.

E. S. Smith, Jr. Automatic Regulators, Their Theory and Application. *Transactions A.S.M.E.*, Vol. 58, May 1936, pages 291-303. Discussion: *Transactions A.S.M.E.*, Vol. 59, 1937, pages 125-141.

THE STEADY STATE

With these elementary principles in mind, we shall first study the steady state of heat transfer.

Suppose that in a plant having a corresponding controller attached to it, the temperature is temporarily remaining constant because the demand and supply are at the moment both steady. Let us move the indicator or measuring element of the controller an infinitesimal amount $d\theta$, thus changing the heat input an amount dq, and hold the element forcibly by hand in this new position until the temperature has become steady at a new value. Now if the element is suddenly released it will move in the opposite direction from the way we were holding it to a position differing from the original one by an amount $-(d\theta)_a$, the minus sign indicating the primary function of the controller to combat a change. The relation between $d\theta$ and $(d\theta)_a$ is simply

$$(d\theta)_a = -sd\theta \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where s is a constant of proportionality.

The change $(d\theta)_a$* resulted from a change dq in the heat input. Now, if s is to be truly a constant, so that equation 1 is to hold for all values of load and positions of the controller, then the controller must be so designed that dq will vary according to the relation between q and θ in the uncontrolled plant—uncontrolled because during the test just described the controller is prevented (held) from functioning. In the continuous process, assuming that the heat lost is small compared with the total required, the temperature of the uncontrolled plant varies according to the equation:

$$q = L(\theta - \theta_0) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where θ_0 is a reference temperature.

At any constant value of L at which the holding test is made:

$$dq = L(d\theta)_a \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and from equation 1:

$$dq = -Lsd\theta \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Dividing equation 4 by equation 2 eliminates the variable L, and we get:

$$dq/q = -sd\theta/(\theta - \theta_0) \quad . \quad . \quad . \quad . \quad (5)$$

and integrating:

$$(\theta - \theta_0)^s = k/q \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This equation may be called the static equation of a controller designed to have the constant sensitivity s when applied to control a continuous process. It states that the heat input is *corrected* proportionally to the s power of the temperature, or, referring to the differential form, equation 5, a fractional change in temperature under constant load results in a fractional change in heat input of s times as much in the opposite sense. Note that each side of equation 5 is dimensionless, and that s in these equations is revealed as the sensitivity of the controller in a commonly-accepted meaning of sensitivity.

A simple equation in θ, L showing how the temperature of the controlled plant varies with L is obtained by combining equations 2 and 6:

$$(\theta - \theta_0)^{s+1} = k_2/L \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Differentiating, and dividing by equation 7:

$$\frac{d\theta}{\theta - \theta_0} = \frac{-1}{s+1} \cdot \frac{dL}{L} \quad . \quad . \quad . \quad . \quad (8)$$

This equation states that the fractional change in temperature, or load error $d\theta/(\theta-\theta_0)$, or simply $d\theta/\theta$ where θ is large compared to θ_0, of a corresponding controller of sensitivity s controlling a continuous process, is $1/(s+1)$ times the opposite fractional change dL/L in the load. For example, if s is equal to 19, a 20% change in load results in a 1% change in temperature. Equation 8 in this dimensionless form will be found useful, for the assumptions made in the simple derivation are only slightly restrictive.

The so-called batch process may be regarded in the present state of theoretical development as one in which the heat input is equal to the heat lost, this loss being a function of temperature. We shall select the case in which heat is being supplied in fuel form from an uncontrolled supply pressure p, through a valve having a controllable variable opening A, and assume that the heat supply is proportional to Ap, as a sufficient approximation. We might have selected, on the other hand, electric heating with controllable current at an uncontrolled voltage. For the present purpose it will be sufficient to write, without violent assumptions, that

$$A_c p = k_3\theta^n \quad . \quad . \quad . \quad . \quad . \quad (9)$$

for the equation of the uncontrolled plant, that is, the position of the control valve remains at that corresponding to a constant opening, of area A_c, and the heat supply is $q = A_c p$. In equation 9, n is a constant usually less than 2. Suppose however that we propose to manipulate the controller by hand as we did to demonstrate the action of the controller on the continuous process, thus altering A while p remains constant at p_c. Then for the equation of the "manipulated" plant we have

$$Ap_c = k_3\theta^n \quad . \quad . \quad . \quad . \quad . \quad (9')$$

While the temperature of the plant is for the moment, steady, let us move the indicator or measuring element an infinitesimal amount $d\theta$, thus changing the heat input an amount proportional to $p_c dA$, and hold the element forcibly by hand in this new position until the temperature has become steady at a new value. As before, when the element is released it will move to a position differing from the original one by an amount $-(d\theta)_a$. The relation between $d\theta$ and $(d\theta)_a$ could be represented by equation 1, but in this case the thermal load, which is equal to the heat lost, has

*This is the same as Ivanoff's "potential temperature."

DEFINITIONS OF SYMBOLS

A = area, variable
A_c = area, constant
a = thermal diffusivity
c = specific heat
k = conductivity only in $a = k/c\rho$
L = thermal load, e.g. lbs. per second times average specific heat
λ = wave-length
ln = abbreviation for $\log_e$
n, k, k_1, etc., a, constants
p = pressure, variable
p_c = pressure, constant
Q = volume rate of flow
q = heat input, e.g. watts, or Btu per second
q_m = amplitude of q
R = resistance to flow
ρ = density
s = sensitivity, see text
s' = an apparent sensitivity
t = time
T = period of oscillation in seconds
θ = temperature or small departure from a fixed value
θ_0 = θ at $x = 0$, also reference temperature
θ_m = amplitude of θ_0
θ_L = θ at $x = x_L$
θ'_m = amplitude of θ_L
v = velocity
V = volume
x = variable distance

changed with the temperature, and we shall write the relation

$$(d\theta)_a = -s'd\theta \quad . \quad . \quad . \quad . \quad (10)$$

where, comparing it with equation 1, s' is the apparent sensitivity. From 9′:

$$p_c dA = k_3 n\theta^{n-1} (d\theta)_a \quad . \quad . \quad . \quad . \quad (11)$$

and from 10:

$$p_c dA = -k_3 n s'\theta^{n-1} d\theta \quad . \quad . \quad . \quad (11')$$

and from 9′:

$$dA/A = -ns'd\theta/\theta \quad . \quad . \quad . \quad . \quad (12)$$

and integrating:

$$\theta^{ns'} = k_4/A \quad . \quad . \quad . \quad . \quad (13)$$

or putting $ns' = s$:

$$\theta^s = k_4'A \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Equation 13 may be called the static equation of a corresponding controller designed to have the constant sensitivity $ns' = s$ when applied to control a batch process. It states that the heat input is corrected proportionally to the ns' power of the temperature, or, referring to equation 12, a fractional change in temperature results in a fractional change of heat input of ns' times as much, in the opposite sense.

Referring again to equations 9 and 9′, we may write

$$Ap = k_3\theta^n \quad . \quad . \quad . \quad . \quad . \quad (15)$$

for the equation of the controlled plant where, from equation 13:

$$A = k_4/\theta^{ns'} \quad . \quad . \quad . \quad . \quad (16)$$

or, combining 15 and 16

$$k_4 p/\theta^{ns'} = k_3\theta^n \quad . \quad . \quad . \quad . \quad (17)$$

or

$$\theta^{ns'+n} = k_5 p \quad . \quad . \quad . \quad . \quad . \quad (18)$$

and

$$\frac{d\theta}{\theta} = \frac{1}{ns' + n} \cdot \frac{dp}{p} = \frac{1}{s + n} \cdot \frac{dp}{p} \quad . \quad (19)$$

The effects of self-regulation[4] are seen in the factor $s + n$ of equation 19 in place of $s + 1$ in equation 8, and the factor s', equal to s/n in equation 10 in place of s in equation 1. The expression "self-regulation" is used to describe the retarding effect of the change in heat lost that accompanies a change in temperature. For example, if the pressure of fuel supply to an uncontrolled batch process rises, the temperature will rise, but this will result in an increase in heat lost, which will in turn tend to prevent the rise in temperature. The effect is negligible in the continuous process.

Equation 19 (compare equation 8) states that the fractional change in temperature or heat-potential error $d\theta/\theta$ of a corresponding controller of sensitivity s applied to a batch process is $1/(s + n)$ times the fractional change dp/p in the heat potential. The equation, likewise equations 12 and 13 will be used cautiously for drawing conclusions.

Before passing on to a study of the varying state, we should like to make a few observations that may be of interest to those readers who are familiar with the general subject, and in particular, those who have been following the contributions by the A.S.M.E. Committee on Industrial Instruments and Regulators. A static equation of a "corresponding" regulator including s, the sensitivity, as a constant must take a form similar to equation 6 for the continuous process. That is, it must be built up after eliminating the expression for the load, otherwise s will not be constant but will vary with load or demand. Not only does the choice of these equations offer a more readily understandable starting point in a study of temperature control, but, so far as we know, they have made it possible for the first time to derive simple expressions for load error. These expressions are simple, because fundamentally an expression for load error can be simple only if based on an equation in which s is truly a constant. Thus if s varies with load, then an expression for the load error will involve load as a variable, and the simplest expression must be limited to a specified load, or, what is the same thing, a specified position of the regulator in regard to the limits of the throttling zone, e.g. half-way between the limits.[5] However we do not propose to use the above equations for a study of dynamic conditions, because their combination with harmonic functions would lead to cumbersome forms.

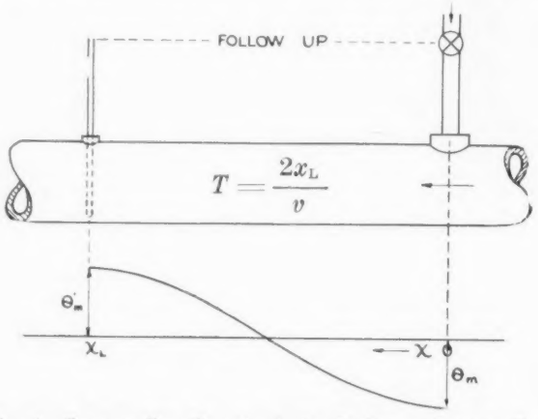


Fig. 1. Corresponding Control of the Continuous Process. Undamped Temperature Wave. Equations 20 and following.

THE VARYING STATE

Our first consideration in beginning a study of the dynamic characteristics of a controller or its combination with the plant, is to select conditions which will teach us the most in the simplest way. Some authors begin with the selection of a standard disturbance. There are a number of objections to this method of approach. (1) The mathematics is needlessly complicated, no matter what form is assigned to the disturbance. (2) Temperature waves from the heat source to the thermometer travel so slowly that there are no inertia effects of appreciable magnitude in the controller or any of its parts, that must be studied, in order to learn how the controller will respond to the disturbance. (3) Theoretically, it may be considered as a fault in design if a controller does not respond to a disturbance properly when it is adjusted as to sensitivity and damping at the preferred values. For example, excessive damping may be required to counteract the deleterious effect of an excessive dead zone, making it necessary to release the damping when a strong disturbance arises.

Let us begin, then, with the oscillating condition.*

A *fourth* simple *principle* of automatic temperature control is that oscillation or hunting will persist only if each successive wave of temperature reaching the thermometer is at least as large as its predecessor, and if successive

[4] W. Trinks, Governors and the Governing of Prime Movers, Chap. XV, D. Van Nostrand Co., New York, 1919.

*Ivanoff used a square wave as his standard disturbance, represented by a Fourier's series, and did not use a harmonic oscillation for the standard, as stated in a recent contribution to the A.S.M.E. committee mentioned above, but he did begin with the oscillating condition.

[5] C. E. Mason & G. A. Philbrick. Automatic Control in the Presence of Process Lags. *Transactions A.S.M.E.*, Vol. 62, No. 4, May 1940, pages 295-304. Discussion: pages 305-308.

aves decrease they will die out, and there will be found a mping force somewhere in the system. The combination f controller and plant may be regarded as two oscillating nits centered at the valve and the thermometer, like two winging pendulums joined with a spring and a dashpot, although the likeness is remote and we will not be concerned with it further.[6]

Referring to Fig. 1, suppose that water to be heated is flowing at constant velocity in the pipe from valve to thermometer, that heat enters at the valve, and that the position of the valve is made to correspond with the temperature of the thermometer, by means of a "follow-up" linking the two. We shall assume for the moment that there is no lag of the thermometer, no damping device in the follow-up (the valve moves in instant response to the thermometer), and no heat lost from the water between the valve and the thermometer. If now we find the controller hunting, then (cf. equation 6), when the thermometer is at its highest point of swing corresponding to the crest of a temperature wave, the valve is at its smallest opening corresponding to the trough of the wave which will presently reach the thermometer, and a sensitivity of unity is just sufficient to maintain hunting. Such a sensitivity maintains each successive

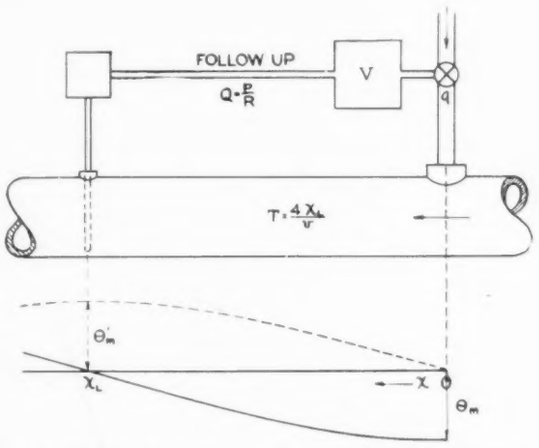


Fig. 2. Corresponding Control of the Continuous Process. Undamped Temperature Wave. Damped Regulator. Equations 27 and following.

wave at a constant amplitude, according to the definition of sensitivity. Our controller now has the poor characteristic of large load error, in fact equal to ½ the change in load (equation 8), and hence the sensitivity must not be reduced to stop hunting. On the other hand the sensitivity should be increased while some other means is found to stop hunting. There are unavoidable damping forces in any real case, such as attenuation of the temperature wave as it passes through the wall of the thermometer inclosure, accompanied in this case, unfortunately, by delay in response of the thermometer. However this single effect may permit the use of sensitivities well above unity for the continuous processes. Still higher sensitivities are made possible through the use of various damping devices at the valve or in the follow-up system. Any of these should avoid, of course, the imposition of any time delay in excess of that corresponding to the damping action.

Referring again to Fig. 1 and assuming as before that there is no lag at the thermometer, no heat lost between the valve and the thermometer, and no damping device used in the "follow-up," sustained temperature waves starting at the valve and passing the thermometer can be represented by the well known equation:

$$\theta = \theta_m \cos 2\pi (t/T - x/\lambda), \quad . \quad . \quad . \quad (20)$$

in which θ is the departure of the temperature from a fixed value. This equation defines θ for all values of t and x, a stationary wave being defined for any time t_1 and the oscillations about any point x_1. Putting $\theta = \theta_0$ in the plane $x = 0$:

$$\theta_0 = \theta_m \cos(2\pi t/T) \quad . \quad . \quad . \quad (21)$$

For small variations $s\theta_L = -\theta_0$, and if $s = 1$,

$$\theta_L = -\theta_m \cos(2\pi t/T) = \theta_m \cos(2\pi t/T - \pi) \quad (22)$$

where θ_L is now the value of θ in the plane $x = L$.

From 20 putting $x = x_L$, and 22,

$$2\pi x_L/\lambda = \pi \text{ and } x_L = \lambda/2 \quad . \quad . \quad (23)$$

The thermometer is one-half wave length from the valve.

The velocity of the wave is $v = \lambda/T = 2x_L/T$. $T = 2x_L/v$

It is apparent without proof that the velocity of the temperature wave is the same as the velocity of the stream of liquid, and that in this case the period T is twice the time lag x_L/v.

If s is less than 1, then each successive wave is smaller than the preceding one, and the train of damped waves is represented by

$$\theta = \theta_m e^{-kx/\lambda} \cos 2\pi (t/T - x/\lambda), \quad . \quad . \quad (24)$$

where $\lambda = 2x_L$ as before.

$$\theta_m/\theta'_m = e^{kx_L/\lambda} = e^{k/2} = s \quad . \quad . \quad . \quad (25)$$

The so-called logarithmic decrement, or log of the ratio of succeeding crests (a full wave length apart), is

$$k = 2 \ln s \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Referring now to Fig. 2, let us suppose that there is interposed, between the thermometer and the valve, a damping device consisting of a compressed air line and tank, the line having a resistance to flow. For our present purpose we may write,

$$Q = p/R \quad . \quad . \quad . \quad . \quad . \quad (27)$$

where Q is volume rate of flow of air in the connecting line, resulting from a departure p in pressure from a fixed value, and R is the resistance to flow. Also, for small departures, as before,

$$-s\theta_L = p \quad . \quad . \quad . \quad . \quad . \quad (28)$$

taking the constant of proportionality as unity.

If the position of the valve is determined by the pressure in the tank, then,

$$\frac{dq}{dt} = \frac{Q}{V} = \frac{-s\theta_L}{RV} = \frac{-s}{RV}\theta'_m \cos 2\pi(t/T - x_L/\lambda) \quad (29)$$

$$q = -\int \frac{s\theta_L}{RV}\,dt = \frac{-sT\theta'_m}{2\pi RV} \sin 2\pi(t/T - x_L/\lambda) \quad (30)$$

$$= \frac{sT\theta'_m}{2\pi RV} \cos\left[2\pi(t/T - x_L/\lambda) + \pi/2\right]$$

$$= L_1\theta_0 = L_1\theta_m \cos 2\pi t/T$$

Then, $2\pi x_L/\lambda = \pi/2$, $\quad x_L = \lambda/4$, ... (31)

and $$\frac{\theta_m}{\theta'_m} = \frac{sT}{2\pi L_1 RV} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

[6] J. H. Morecroft, Principles of Radio Communication, Third edition. John Wiley & Sons, New York, 1933. Pages 264 and following.

the ratio of the amplitude at $x = 0$ to that at $x = x_L$.

The equation of the damped wave is:

$$\theta = \theta_m e^{kx/\lambda} \cos 2\pi \, (t/T - x/\lambda) \quad . \quad . \quad (33)$$

and from 31 to 32

$$e^{k/4} = sT/2\pi L_1 RV \quad . \quad . \quad . \quad (34)$$

In this case the period $T = 4x_L/v$ or four times the time lag, whatever the degree of damping determined by the sensitivity s, the capacity V of the tank, and the resistance R to flow of air, provided that the damping is small enough to permit decaying oscillations following a disturbance. For example, relatively rapid recovery will result if the first overswing is 10% of the departure, and the second or return overswing is 1%. Commercial controllers are equipped with

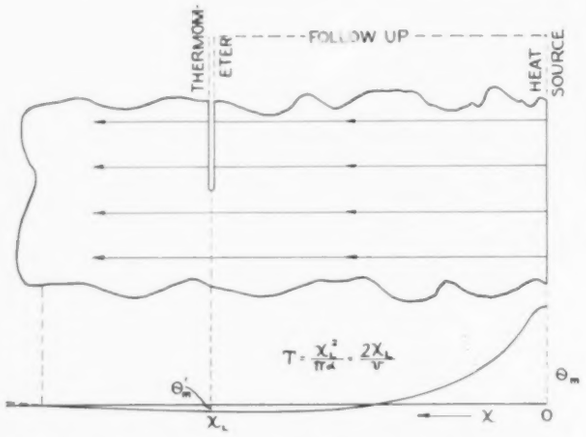


Fig. 3. Corresponding Control with Attenuation of Temperature. Damped Temperature Wave. Equations 35 and following.

means for adjusting sensitivity and damping, and for this reason extension of the analysis beyond this point is of interest mainly to the instrument designer. General interest lies in the observation that damping permits the use of high sensitivity, which results in small errors caused by changes in load.

Delayed response accompanies damping of a controller, hence we come to a *fifth principle*, that high sensitivity made possible for the continuous process by damping the controller is incompatible *per se* with quick response of the controller to a disturbance. It is possible, of course, to incorporate in the controller a damping release which functions when a selected value of the rate of disturbance is exceeded. Such a device will result in overshooting the control point by a large amount following the first return from the disturbance, and under extremely unsteady conditions to be controlled the releasing device may function so frequently that no effective damping remains.

The time lag met with in the continuous processes, as illustrated in Fig. 1, unaccompanied by any attenuation of the temperature wave presents one of the more difficult problems in temperature control. However, before discussing further the case of the continuous process, we shall proceed to the consideration of the case of temperature attenuation met in heat conduction, particularly in the heat treatment of solid charges such as the annealing of metals and alloys. The first principles are learned from the study of heat conduction through solids, the simplest case of this being linear flow of heat.

Again let us suppose that the controller is hunting, that is, maintaining a train of temperature waves traveling from the heat source to the thermometer. Referring to Fig. 3, the thermometer within the solid conductor is connected by an undamped follow-up device to the heat source covering the plane face. An experimental approximation to this arrangement furnishes the observation that the variation of temperature of the heated face closely follows a simple harmonic function of time, and the train of waves traversing the solid may be represented by the classical equation, in the most convenient form we have found:[12, 13]

$$\theta = \theta_m e^{-x\sqrt{(\pi/\alpha T)}} \cos \left[\, (2\pi t/T - x\sqrt{(\pi/\alpha T)} \, \right] \quad . \quad (35)$$

where α is thermal diffusivity. If there is no lag of the thermometer at distance x_L from the source and no delay in the "follow-up" then, as before, for the corresponding controller,

$$x_L = \lambda/2 = \sqrt{(\pi\alpha T)} \quad . \quad . \quad . \quad . \quad (36)$$

by comparison of equation 35 with equation 20 or 24.

The amplitude at $x = 0$ is θ_m, and at $x_L = \lambda/2$ is

$$\theta'_m = \theta_m e^{-\lambda\sqrt{(\pi/\alpha T)}/2} = \theta_m e^{-\pi} \quad . \quad . \quad (37)$$

The ratio of θ'_m to θ_m is $e^{-\pi}$, that is, the wave is attenuated at the thermometer to 1/23.1 of its amplitude at the source, hence in this case an undamped controller must have a sensitivity of 23.1 to be able to maintain the oscillations. In a real case, the thermal capacity of the heating element will introduce further powerful damping, and with a controller of negligible dead zone, sensitivities of over 100 are required to maintain hunting.

Further study of these equations leads to interesting results. The time $T/2$ required for the wave to travel from the source to the thermometer is found from equation 36 to be

$$T/2 = x_L^2/2\pi\alpha \quad . \quad . \quad . \quad . \quad (38)$$

Putting x_L equal to 1 cm., the time lags for a few substances having different diffusivities, α, are given in Table 1:

TABLE 1

Substance	α	t(sec.)
Brick	0.005	32
"	0.01	16
"	0.1	1.6
Iron	0.16	1
Aluminum	0.8	0.2
Copper	1.1	0.15
Silver	1.7	0.09

According to equation 38 the lag depends only on the thickness of the plate and the diffusivity of the material, and not on the amplitude of the wave. Thus, again, the period of oscillation of the controller is independent of the sensitivity, assuming that the dead zone is negligible.

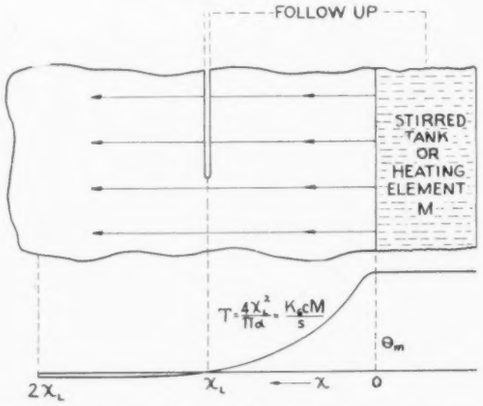


Fig. 4. Corresponding Control with Attenuation of Temperature and Real Source. Equations 39 and following.

In Fig. 4, the heating element or source has a thermal capacity cM, and may be an electrical resistor or strongly stirred bath against the surface of the solid conductor. If x and t are measured as before, then equation 35 can repre-

nt the temperature wave in the solid, and we must next determine the phase relation between θ_0 at the surface and the controlled input.

$$\text{At } x = 0, \qquad \theta_0 = \theta_m \cos 2\pi t/T \quad . \quad . \quad . \quad . \quad (39)$$

$$d\theta_0/dt = q/cM = -\,2\pi\theta_m/T \cdot \sin\,(2\pi t/T) \qquad (40)$$
$$= 2\pi\theta_m/T \cdot \cos\,[\,(2\pi t/T) + \pi/2]$$

That is, when θ_0 is a maximum q has been positive and is passing through zero. When q thus leading θ_0 by one-quarter period and leading θ_L at the thermometer by one-half period, then the thermometer finds itself at one-quarter wave-length from the surface of the solid and $T = 4x_L/v$, or four times the time lag between the temperature of the source and that of the thermometer.

Referring to equations 36 and 37, in the present case:

$$\theta'_m = \theta_m e^{-\lambda\sqrt{(\pi/\alpha T)/4}} = \theta_m e^{-\pi/2} = \theta_m/4.8 \quad . \quad (41)$$

that is, the wave is attenuated to 1/4.8 of its initial value, whatever the value of the sensitivity of the controller, capacity of the source, or properties of the solid. But this does not determine the minimum sensitivity required to maintain oscillations.

Noting that this case resembles the so-called batch process and referring to equations 13 and following, we may write, for small oscillations:

$$s\theta_L = -\,k_6 q \quad . \quad . \quad . \quad . \quad (42)$$

and

$$s\theta'_m = k_6 q_m \quad . \quad . \quad . \quad . \quad . \quad (43)$$

From equation 40:

$$q = 2\pi c M\theta_m/T \cdot \cos\,[\,(2\pi t/T) + \pi/2] \quad . \quad . \quad (44)$$

and

$$q_m = 2\pi c M\theta_m/T \quad . \quad . \quad . \quad . \quad (45)$$

Substituting for q_m from equation 43:

$$s\theta'_m/k_6 = 2\pi c M\theta_m/T \quad . \quad . \quad . \quad . \quad (46)$$

and from 41

$$s\theta'_m/k_6 = 9.6\,\pi c M\theta'_m/T \quad . \quad . \quad . \quad (47)$$

or

$$s = k_7 c M/T \quad . \quad . \quad . \quad . \quad (48)$$

and from 36

$$s = k_8 \alpha c M/x_L^2 \quad . \quad . \quad . \quad . \quad (49)$$

In conducting the analysis of the last case toward equations 48 and 49, it has been our purpose to show why, in the so-called batch process, the sensitivity can take high values, even in a controller having no damping arrangement. The analysis applies also to those continuous processes in which the load, or "through-put," of processed material is small compared thermally with the heat loss. Examples of such continuous processes are (1) manufacture of rubber filaments, (2) continuous heat treatment of steel wire, and (3) tunnel kiln processes for the slow firing of ceramic materials.

The last few equations including 41 show that the attenuation of a temperature wave through the protection tube of a thermocouple in a furnace or liquid bath may be as much as 80%. Thus the oscillations of the temperature of the outer surface of the tube may be some five times as great as the indicated oscillations.

We have, so far, treated a limited number of typical cases of automatic temperature control, but believe that we have demonstrated a new treatment which not only is relatively easily understood, but affords useful results reasonably approximating real cases. We believe also that the corresponding method of control stands out as the most important and most widely used, (possibly second only to "on-and-off" control) and that a study of the one method suffices for learning the fundamentals. In passing, a little consideration shows that in on-and-off control, the thermometer will generally find itself one-quarter wave-length from the source, and not one-half wave, as Ivanoff[1] considered by assuming a square wave, i.e. no capacity effect that is not accompanied by attenuation. Our treatment is not generally in disagreement with the descriptive method of Bristol and Peters[7] nor with those authors who would stress the special hydraulic problems accompanying the use of a valve to control flow against varying back-pressures or resistances. It is admitted without argument that there may be a deal of engineering required for solving many of the problems in industrial process control. We are concerned here with the physics of the problems, not the mechanical design of plant, instruments or accessories. Possibly more has been written about the mechanical design of governors, or speed regulators, than about the physics of automatic temperature control, and the former should not be confused with the latter.

Nearly all problems in temperature control that are solved, have been solved experimentally, both in regard to the construction or selection of control equipment on an experimental basis, and the adjustment of the trial instruments as to sensitivity, damping, speed of automatic reset,[8] response to change of load or control point, and variations of these factors under different conditions. An analytical method of study of the theories of automatic temperature control will make for more intelligent judgment in adjusting a controller, but we would hesitate to try to solve a problem in advance of the practical trial to the point that prescribed values of the many variables involved could be set down with nicety. A practical difficulty is met, for example, in the generally unavoidable dead-zone of a controller. We have not avoided mathematical treatment of the dead zone because of indolence but of indifference. It should generally be regarded as an imperfection, to be made as small as possible.

An ideal controller for experimental study of the theory is one incorporating the Gouy principle[9] because it furnishes "corresponding" control, has no dead zone whatever, and makes possible the selection of sensitivities of exceedingly high values. It has been found to be the most satisfactory device for precision control in the laboratory by Sligh[10], other members of the staff of the National Bureau of Standards, Roebuck[11], and many metallurgists who are in charge of creep tests. Our treatment of corresponding control is well adapted to a study of the Gouy principle or of a controller utilizing it. The sensitivity, as we have used the term, and with a meaning which is acceptable to many others, is inversely proportional to the stroke of the Gouy oscillator, which determines the limits of the throttling zone, and the sensitivity is made constant by imparting to the oscillator a motion in accordance with equation 6. The sensitivity can be expressed also as inversely proportional to the velocity of the oscillator at any part of its stroke, and the period of oscillation is made short enough not to enter into the analysis.

[7]E. S. Bristol & J. C. Peters. Some Fundamental Considerations in the Application of Automatic Control to Continuous Processes. *Transactions A.S.M.E.*, Vol. 60, No. 8, Nov. 1938, pages 641-650. Discussion: *Transactions A.S.M.E.*, Vol. 61, No. 4, May 1939, pages 358-363.

[8]Compare references 1 and 3.

[9]C. O. Fairchild. Note on the Throttling of Electric Heat. *Instruments*, Vol. 10, Dec. 1937, pages 305, 317.

[10]T. S. Sligh, Jr. Some Characteristics of the Gouy Thermoregulator. *Journal Am. Chemical Society*, Vol. 42, Jan. 1920, pages 60-68.

[11]J. R. Roebuck. A Sensitive Flexible Thermostat. *Review of Scientific Instruments*, Vol. 3, 1932, pages 93-100.

[12]Schack, Goldschmidt and Partridge, Industrial Heat Transfer, John Wiley & Sons, New York, 1933. Note that in our analysis, the velocity of the train of waves is determined by a and x_L and that our equation 38 supersedes Schack's equation 122.

[13]W. E. Byerly. Elementary Treatise on Fourier's Series, Ginn & Co., New York, 1893.

Ingersoll & Zobel. Theory of Heat Conduction, Ginn & Co., New York, 1913 (out of print).

For bibliography on regulation see publications by A.S.M.E. committee referred to in reference 3, and on heat transfer see reference 12, also W. H. McAdams, Heat Transmission, McGraw-Hill (1933), and *Journals* of Am. Soc. Heat. & Vent. Engrs. and of Am. Soc. Refrig. Engrs.

Industrial Pyrometry

Third instalment of new and completely revised edition of "Temperature Measurement and Control." The subject of pyrometry will be concluded with Optical Pyrometers, Pyrometric Cones, Miscellaneous Pyrometers, etc., in the December instalment which will also include a continuation of Temperature Control Principles and Modes of Control.

By M. F. BEHAR

CHAPTER X

RADIATION PYROMETRY

(NON-SELECTIVE EMISSION AND RECEPTION)

1. "Radiation"—in Quotation Marks.

At the time that the Thirteen Colonies decided to form a new nation, there were high-temperature industries. There were measurement-minded engineers. Among the scientists there were physicists who took interest in the problems of ceramic and metallurgical industries. Thus, even in those days, numerous men appreciated the need of measuring the temperatures inside kilns and furnaces *from the outside*. Experimenters installed thermometers near peep-holes—with lenses, mirrors, tubes, diaphragms, etc.—in attempts to find an arrangement whereby the furnace temperature could be unmistakably read on a thermometer not exposed to destructive conditions.

All these attempts failed.

But the modern radiation pyrometer is—essentially—a device of just that kind: a thermometer with an arrangement of lenses, mirrors, tubes, diaphragms, etc.

It is not improbable that one of the first experimental set-ups, which one of our great-great-great-grandfathers tried out and discarded, could be made to work today. Certain old flying machines which could not fly when they were built can be flown today. Reason: better knowledge of the basic laws of aerodynamics. So it is with radiation pyrometry. As a matter of fact, this comparison does not do justice to the physicists who have derived and formulated the radiation laws, for there are no more important gaps to be filled, whereas aeronautical science—in comparison—is like Swiss cheese.

It may even be said that *all* gaps have been filled in the formulation of the *basic* radiation laws—the laws which describe in mathematical terms the behavior of the ideal emitter and of the ideal pyrometer receiver. (Attaining fifth-decimal accuracy is a matter of refinement of *practice;* the basic laws stand intact; only the values of the "constants" are revised.) Moreover, the collateral knowledge of the behavior of non-ideal emitters and non-ideal pyrometer receivers is so exact, the amount of this knowledge is so great, and in recent years it has been so well organized that almost any hasty makeshift of "a blackened thermometer in front of a furnace peep-hole" could be calibrated. This is important because in practice we never find ideal emitters and we can't buy ideal receivers. We never meet 'total radiation" in industrial processes and many of the supposedly non-selective pyrometers we use in industry are more selective with regard to total radiation than some optical pyrometers are selective with regard to visible radiation.

(Unbelievable? Nevertheless demonstrable: Many radiation pyrometers on the industrial market are more selective with regard to total radiation than some optical pyrometers are selective with regard to luminous flux. But it doesn't matter much, as we shall see.)

Before discussing radiation pyrometers it is well to take up briefly the subject of radiation pyrometry, but in order to open that subject it is necessary to take up the words Radiation, Thermal Radiation, Radiant Energy, etc. Otherwise, even the tabloid presentation of Figs. 1 and 2 would not convey the right ideas. (But Figs. 1 to 5 have been drawn for visually-minded readers who will skim through the text anyway.)

According to the Standard Dictionary of the English Language (1938 edition) radiation is: "1. The act of radiating, or the state of being radiated; emission or divergence, as of rays in all directions possible from a common source or center. 2. *Physics.* (1) The transference of energy in straight lines through regions not occupied by ordinary matter or through matter which is not affected by the transmission: opposed to *conduction.* (2) Energy in process of such transmission; radiant energy; especially, light and radiant heat."

In Van Nostrand's Scientific Encyclopedia (1938), the reader looking up "Radiation" is told to look under *two* titles: "Electromagnetic Radiation" and "Thermal Radiation." The first of the two brief articles explains Maxwell's wave theory of light, gives "types" from gamma rays to Hertzian radiation—and ends with a reference to the second article, which starts as follows: "All bodies that are

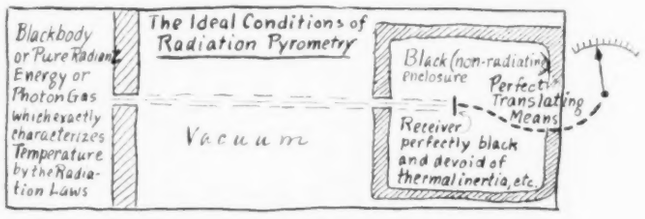

The Ideal Conditions of Radiation Pyrometry
Blackbody or Pure Radiant Energy or Photon Gas which exactly characterizes Temperature by the Radiation Laws
Vacuum
Black (non-radiating) enclosure
Perfect Translating Means
Receiver perfectly black and devoid of thermal inertia, etc.

Fig. 1

not at absolute zero emit radiation excited by the thermal agitation of their atoms or molecules. . . . This thermal radiation ranges in wave-length from the longest infrared to the shortest ultraviolet rays. . . ." (Thus, although treating the two subjects separately, this authority implies that thermal radiation is in no wise different from electromagnetic radiation.)

In the latest (14th ed.) Encyclopædia Britannica there is a long (4200 words) and highly informative article by Andrade entitled "RADIATION, RAYS." The famous English scientist states: ". . . We might distinguish between the two classes by agreeing to confine the term radiation to electromagnetic waves, and to restrict the term rays to streams of particles, but while a tendency in this direction is traceable it is by no means correct to represent this convention as one invariably used by the experts. . . . In a previous edition of the *Encyclopaedia* electromagnetic radiation was dealt with, in different aspects, both under the heading RADIATION and under the heading RAY."

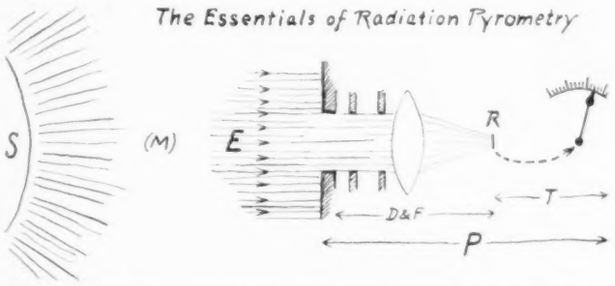
Chambers's Technical Dictionary (1940) has: "**radiant heat** *(Phys.)* Heat communicated to a body by radiation (q.v.)" Also: "**radiation** *(Phys.)*. Energy emitted in the form of electromagnetic waves. These include, in order of increasing wavelength, cosmic rays, gamma rays, X-rays, ultra-violet radiation, light, infra-red radiation, heat rays, and radio waves." The first sentence in this definition is too restrictive, but this is not serious. The second sentence, however, implies differences which do not exist.

In 1937 there was published a 452-page book, "Measurement of Radiant Energy," edited by W. E. Forsythe (of GE's famous lamp lab at Cleveland) under the auspices of the National Research Council. Although evidently compiled for optical and illumination scientists, this work gives the definitions which practical instrument engineers seem to prefer: "Radiation is the transfer of energy by either emitted waves or particles. . . . Radiant energy is the type

f energy which travels in the form of electromagnetic waves. . . . Radiant energy is energy traveling in the form of electromagnetic waves."

Several pages could be filled with quotations showing that the experts disagree even on the definitions of the first two or three basic terms. (There are thirty or sixty terms in the literature—the number increasing with the specialization or ramification of the texts—and disagreements are even more pronounced.)

Some authorities say that radiation is the process of emitting; others say it is what is emitted. Among the latter, some say that radiation includes both waves and particles; others say waves only. Among these latter some say all kinds of waves (electromagnetic, sound, etc.); others say electromagnetic waves only. Some say radiant heat is the heat communicated to a body by radiation; others say it is the heat energy in transit, regardless of the surroundings of the emitter receiver.



S – The Source. *Conventional "rays" merely suggest emission of radiant energy: source need not be incandescent. It need not be a sphere. It need not be a solid. It is included in diagram because its nature determines that of the radiant energy.*

E – The Radiant Energy. *Conventional parallel "beam" indicates that* ***practical*** *radiation pyrometry must not be complicated by problems of hemispherical or other angular measurements. Arrows suggest* ***Flux****, or time-rate of flow. This depends on temperature and on nature of source and (to a lesser degree in practice) on nature of* ***Medium (M)*** *which intervenes between source and pyrometer.*

P – The Pyrometer. *It comprises:* ***R – The Receiver proper****, whose temperature should ideally depend on the source temperature and on nothing else.* ***D&F – Diaphragm-and-focusing arrangement****. The diaphragm (definite area) is essential in order to permit the radiant energy to be sampled and measured as* ***radiant-flux density****; the focusing device (one or more mirrors, lenses, &c.) is not essential but it is an obvious convenience.* ***T – Thermometer*** *for measuring the temperature of the receiver proper R.*

Fig. 2

Reference was made, a few paragraphs back, to the fact that in recent years the "collateral knowledge" (of non-ideal emitters and receivers) has grown and has been "well organized." Perhaps the most valuable part of this recent building of the science of pyrometry, on the simple radiation laws and on the complex effects found in practice, has been the striving by several American workers to define the terms and standardize the symbols which bewilder all pyrometer users who search the scientific journals.* These efforts began shortly after a meeting in Washington in 1936. They have begun to bear fruit. As yet, however, no "official" glossary has been published representing all parties concerned. In the following discussion, therefore, although we depart from the language of the first edition of this book, we shall not hesitate to use some old familiar terms (each of which is being superseded by two or more new terms) and we shall use new terms sparingly.

What the process of radiation may be is not completely understood by science. It seems best to think of radiation as any kind of energy in transit which obeys the laws pertaining to that kind of energy in transit. For example, the field of acoustics deals with one kind of radiation: sound energy traveling in the form of waves through a material medium such as air and obeying a certain set of laws. A stream, ray, or beam of electrons is likewise a kind of radiation, for it can be refracted by magnetic or electrostatic lenses—and it is thereby made to obey the laws of electron optics so accurately that sharp television images and electron microscopes have ceased to be news. As components of atoms, of course, electrons are honest-to-goodness particles of matter; in transit they can be refracted and even diffracted like honest-to-goodness waves — and such waves do not merely carry energy as do water-surface waves but they *are* pure energy. Thus radiation may be particles or waves . . . or *wavicles* — meaning bullets of energy which become bits of matter, or bits of matter which become bullets of energy. Or, simply and more precisely, bundles of energy which remain pure energy when they become constituents of atoms and even when they split, as Einstein puts it in what is accepted as the correct picture. In other words, electrons, protons, positrons and other members of the subatomic family are little chunks of energy. The mechanism whereby atoms and molecules emit and receive these bullets of energy and other bullets of energy known as *photons* of radiant energy differs so much from mechanical analogies that with possibly one exception* nobody as yet has been able to describe it in detail without super-ultra-high-mathematical terms. This would have retarded the progress of radiation pyrometry, but fortunately it is possible for a pyrometer user who lacks mathematical training to grasp *all* the essentials and many of the fine points by studying a few diagrams and by thinking of radiation as energy—not as a process.

This is easier said than done, because the sources of error in radiation pyrometry are the imperfections of the emitters, of the receivers, and (to a smaller extent) of the intervening media. Worse yet, these imperfections are usually *variable*.

All the more reason, we believe, why the radiation pyrometer user should become familiar with microns, photons, lambdas, fluxes, quanta and other such radiant-energy topics which are not discussed in the commercial literature on radiation pyrometry.

In the next section, therefore, there will be described the relations between temperature and *pure energy in transit*.

2. The Exact Relations Between Temperature and Radiant Energy.

It is common to say that heat is radiated from a hotter body to a colder body. This is correct with regard to the net transfer of energy, but radiant energy flows both ways. (However, most radiation laws can be applied without serious error in the majority of practical cases, as if the net transfer were all. Only in precise calibration work do we need to go by the exchange theorem forms of the laws.)

The underlying principle of radiation pyrometry is that heat can only flow from a hotter body to a colder body—never from the colder to the hotter. The flow of heat continues until thermal equilibrium is established, that is to say, until both bodies are at the same temperature. The flow of heat may be radiation (differential), conduction, or convection, or a combination of all three. When it is radiation, therefore, it means that the hotter body emits radiant energy faster than does the colder. The flow continues until equilibrium is established. Nothing can stop it. If a third

*Fifty-two terms and symbols are listed in Table I of "Measurement of Radiant Energy," a compendium edited by W. E. Forsythe (McGraw-Hill, New York, 1937). There are fewer in the two lists prepared by A. G. Worthing (*Journal Optical Society*, Feb. 1939; and *Journal of Applied Physics*, June 1940) but these lists contain new terms not in Forsythe.

*Namely Dr. D'Abro, who seems to have written THE book for the interested reader who has only taken algebra and elementary calculus: "The Decline of Mechanism in Modern Physics." (Van Nostrand, New York, 1939.) This book has nearly a thousand pages —and that's one reason why it's much more readable than austere word-stingy mathematical presentations.

body is interposed where there was a vacuum between two bodies at different temperatures, the newcomer simply changes the process from one of radiation to something else which may be simple or complicated, but unless it definitely alters the temperature difference between the first two bodies, it cannot alter the original tendency.

The relation between the temperature of a body and the rate of emission of radiant energy by this body is independent of the surroundings of this body. This rate depends on the material, the kind of surface, etc., but if these are constant it is an exact function of the temperature of the body.

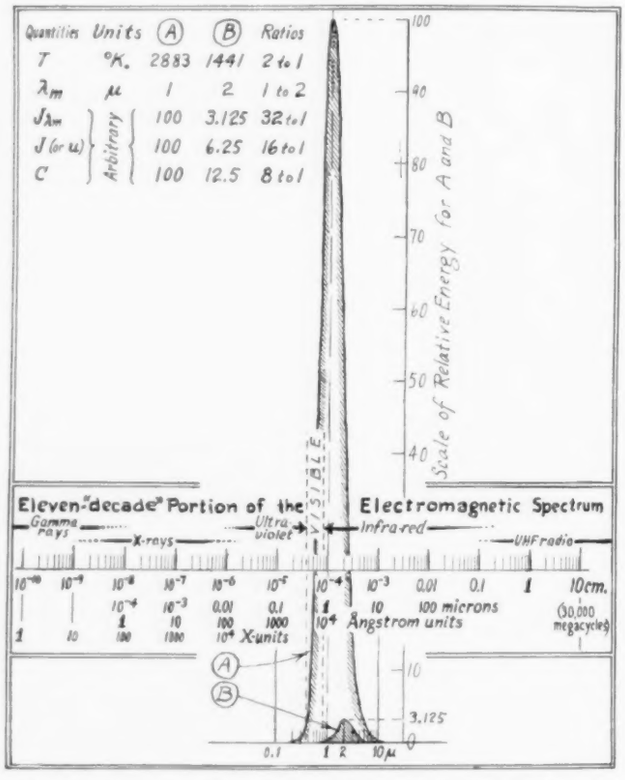


Fig. 3. Crosswise are shown a few regions of radiation, with the visible range in the exact center. The energy curves of two industrial temperatures have their peaks toward the long wave-length side. The sun's curve, if drawn on the same intensity scale, would have it peak about twelve feet above the top of the page and its peak would coincide with the center of the visible range.

It is exactly proportional to the fourth power of the temperature of an ideal body. If the body receives more radiant energy than it emits, its temperature will rise; and vice versa.

Imagine a small sphere inside a larger hollow sphere, the latter at uniform temperature. Eventually, thermal equilibrium will be established between the two spherical surfaces, so that the radiation will be equalized. It will be equalized, but *it will not have stopped:* in the space between the two spheres, radiant energy will be shooting back and forth. Even if we assume a perfect vacuum—total absence of *matter*—there will be something between the two spheres, and its "density" or "intensity" or other property will be uniquely characteristic of the equilibrium temperature which it has brought about. That something may be called a photon gas or radiant energy. Its property which corresponds to temperature may be called by any name. Now imagine the small sphere to vanish: the photon gas or radiation continues to exist, and it continues to "be at the temperature" of the enclosure. Unfamiliar as is the concept, it is helpful to think of *the temperature of radiation.*

As a matter of fact, the marvelous exactness and thorough comprehension of the laws of radiation became possible only when daring scientists rid their minds of the habit of thinking of the temperatures of materials emitting and receiving radiation and began to consider radiant energy itself as endowed with the attribute of temperature.

Of course, radiant energy itself is neither hot nor cold. It is energy in transit and when it falls upon a material body it produces various effects, depending upon its frequencies and upon the frequencies to which the body is tuned. *Light* is the broadcast band to which the human eye is tuned. *Infrared* is a rather ill-defined band of frequencies, too low for visual effects and higher than the frequency-modulation and television channels of today (tomorrow may see a distinct overlap), which band produces the sensation of warmth and is most efficient as carrier of thermal energy in such industrial processes as drying, baking, etc. *Ultraviolet* is the band or region of frequencies too high for visual effects, which produces sun-burn, kills certain germs and makes the coatings of fluorescent lamps emit visible light. Overlapping the ultraviolet region is that of the soft *x-rays*, which shade into the medium (medium-strength and medium-frequency) x-rays; and then come the hard x-rays which overlap the *gamma rays*. At the highest-frequency end of the known electromagnetic spectrum are the *cosmic rays*. A portion of the electromagnetic spectrum is shown in Fig. 3. Never mind for the present the other things shown in that composite picture.

Throughout the foregoing paragraph, the word "frequency" was used, as in radio. And, as in radio, to convert from frequency to wave-length, or vice-versa, we use the familiar constant c, 3×10^{10} cm./sec., which is in round numbers the speed of electromagnetic radiation in vacuo. (The six-decimal value is 299,776 km./sec.) Thus the radiant energy frequency 2×10^{14} vib./sec. corresponds to a wave-length of 5×10^{-5} cm. (This is a familiar enough radiation: it goes by the name of "bluish green.")

For the sake of convenience, workers in pyrometry decided long ago to reduce to a minimum the need of using these powers of ten. Since the "center of gravity" of the spectral region most familiar to pyrometry is somewhere in the near infra-red, say 2×10^{-4} cm. or two millionths of a meter, they adopted the millionth of a meter, or *micron*, as their unit. Its symbol is the Greek letter μ (mu). The symbol for wave-length is λ (lambda). The symbol for frequency is ν (nu). Some recent writers on pyrometry, however, follow spectrometric practice in using the *Angstrom unit*, A.u. (or A. with a dot to distinguish it from argon or area), which is 10^{-8} cm. or 10^{-4} μ. Others use the *millimicron*, mμ, which is 10^{-7} cm., but it gives rise to headaches because it is sometimes printed $\mu\mu$, which really is a micromicron or 10^{-10} cm.

Thus pure total radiant energy is a continuous series, from big to small without gaps, of wave-lengths or of frequencies . . . *or of photons*. It won't be long before radiation pyrometry is taught in terms of photons, and the photon presentation is closer to reality, so here are a few words on the subject. Photons are the quanta of radiant energy—its bullets or wavicles, or elementary corpuscles, or individual components. They are what radiant energy is made of. They range from "big" to "small" according to the spectral region, just like wave-lengths or frequencies, so that a photon of violet light is exactly twice as energetic as a photon of red light if the ratio of frequencies is exactly one to two (as it is near the ends of the visible spectrum). In the radiation from an incandescent body, the ultraviolet photons for which $\nu = 10^{16}$ are each a million times more energetic than the infrared photons for which $\nu = 10^{12}$. A hard x-ray photon ($\nu = 10^{19}$) is a million times more energetic than a medium infrared photon ($\nu = 10^{13}$). Although it's a scientific crime to give a "why" explanation, it's pretty safe to say that this is why x-rays can go through more kinds of matter than can light; and why gamma rays (10^{20}) are used for inspecting large castings; and why cosmic-ray photons (10^{23} or 10^{25}) can be counted one by one with the greatest of ease!

All these bullets travel at the same speed, c, so that since the energy of one bullet is proportional to the frequency of the waves associated with it, something else characteristic of the bullet must be a constant of Nature. That constant is called h, and a bullet or photon or quantum of energy is

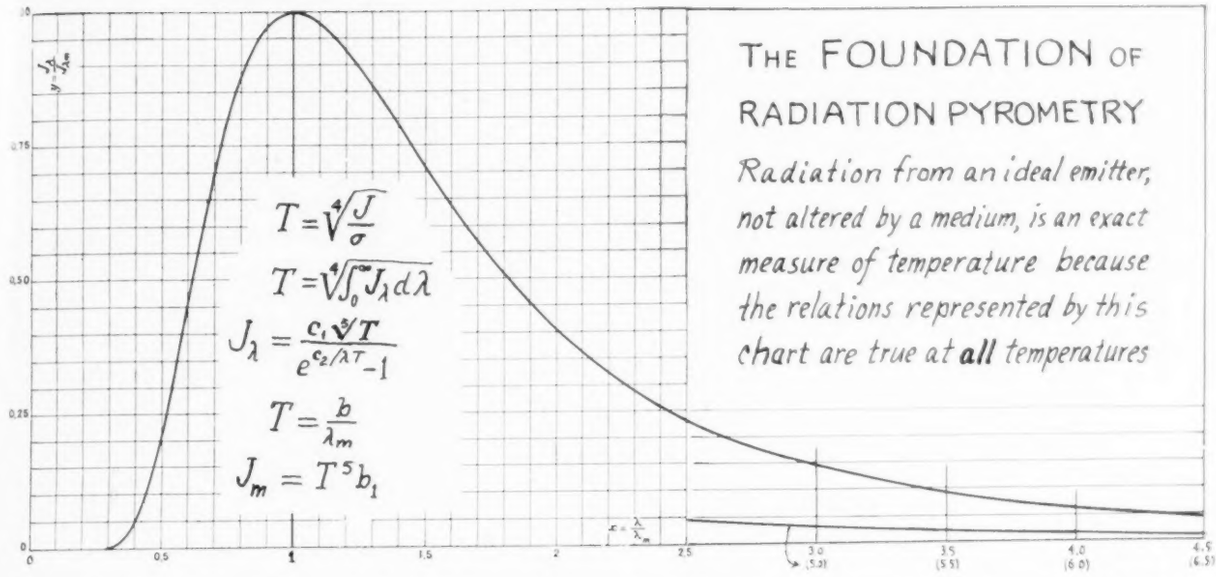

THE FOUNDATION OF
RADIATION PYROMETRY
Radiation from an ideal emitter, not altered by a medium, is an exact measure of temperature because the relations represented by this chart are true at all temperatures
$T=\sqrt[4]{\frac{J}{\sigma}}$
$T=\sqrt[4]{\int_0^\infty J_\lambda d\lambda}$
$J_\lambda=\frac{c_1 \lambda^5 T}{e^{c_2/\lambda T}-1}$
$T=\frac{b}{\lambda_m}$
$J_m=T^5 b_1$

Fig. 4. This is the general portrait of all radiation temperatures. It is called the distribution of energy of the blackbody. In this drawing the horizontal scale (of wave-lengths) makes the wave-length of maximum intensity equal "1." The vertical scale (of intensity) makes the maximum intensity equal "1." Both scales are linear. Both are arbitrary.

$h\nu$. If we go by wave-length units, the momentum of each bullet is h/λ, for $c = \lambda\nu$ and all bullets travel at the speed c. Now then, $h\nu$ is energy and ν is time rate; also h/λ is momentum and λ is length. So what? So h turns out to be energy $\times$ time, or *action*, a mathematical quantity which seems unfamiliar because we never use it in our everyday mechanical or electrical slip-stick computations. Its value is

0.000 000 000 000 655 ergs-seconds.

For further details, reach for any treatment of modern physics. Just remember that radiant energy is a shower of photons.

Now let's get back to the temperature of radiation.

In the foregoing list of regions of the electromagnetic spectrum, the only reference to thermal radiation was an indirect one, in connection with the well-known heat efficiency of the infrared radiations. Does an ideal total-radiation pyrometer respond to all wave-lengths of radiant energy? Or, putting the same question in its converse form, does an ideal emitter radiate all wave-lengths? A glance at Fig. 3 would prompt a negative answer, but let's consult the highest authority. The history-making Bureau of Standards *Scientific Paper No. 250* (1915) on radiation pyrometry declared without ifs and buts:

> "The total radiant energy of a material is represented by vibrations of all possible wave-lengths from zero to infinity."

Does that settle it? No!

Actually, there are ifs and buts!

That green light "carries heat if strong enough" is the usual qualitative description of a readily-observed fact; as are the statements that red light is warm, and blue light cool. Equally well-known is the fact that the extremes of the electromagnetic spectrum do not "carry heat"; neither cosmic rays nor ordinary radio waves are thermal radiation. What then are the extremes of thermal radiation? A partial answer was given in Chapter I where the story of the discoveries which led to the radiation laws was told as a narrative. It was stated that the extremes of the energy distribution curve "dwindle down to zero elevation almost imperceptibly." Two sketches were included, giving the general idea of *blackbody radiation*. In Fig. 3 the limits are not shown (the picture being small) but there is shown the "center of gravity" of industrial radiation pyrometry with reference to the entire electromagnetic spectrum. The two shaded areas roughly represent the curves of two temperatures—not, however, from industrial materials but, as in Chapter I, from *blackbodies*.

If any misnomer was ever adopted by the nineteenth-century scientists, it certainly is "blackbody." The modern concept is that the blackbody is pure radiant energy. To fix that concept in the mind, it is only necessary to think of the radiation that shoots back and forth in a uniform-temperature enclosure. This radiation, and not the material of the enclosure, is the blackbody. If we open a relatively small hole in a wall of the enclosure, the radiation emitted and received through this hole will be blackbody radiation. This

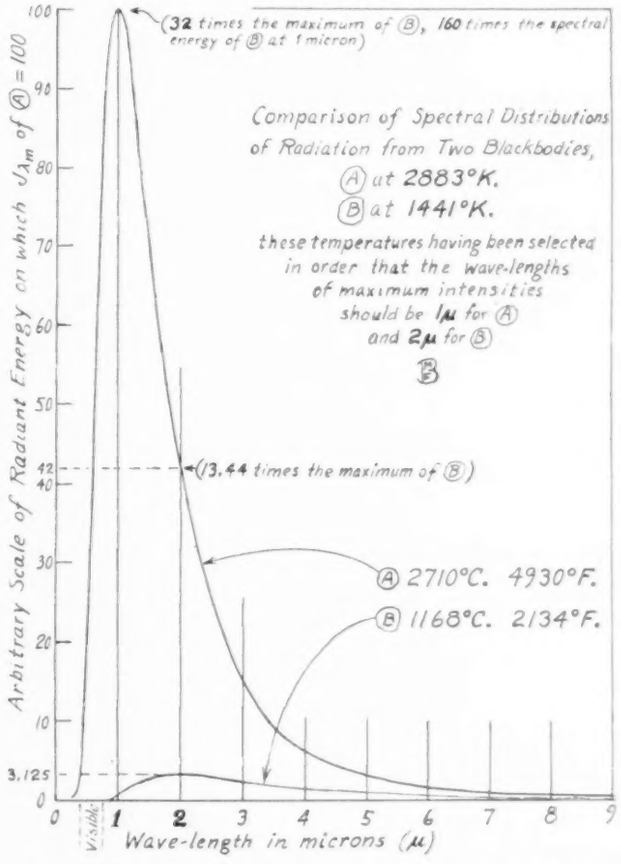

(32 times the maximum of (B), 160 times the spectral energy of (B) at 1 micron)
Comparison of Spectral Distributions of Radiation from Two Blackbodies,
(A) at 2883°K.
(B) at 1441°K.
these temperatures having been selected in order that the wave-lengths of maximum intensities should be 1μ for (A) and 2μ for (B)
(3.44 times the maximum of (B))
(A) 2710°C. 4930°F.
(B) 1168°C. 2134°F.
Arbitrary Scale of Radiant Energy in which J_m of (A) = 100
Wave-length in microns (μ)
Visible
3.125

Fig. 5. Here are blackbody temperatures *A* and *B* of Fig. 3, plotted on linear scales. Note how close to "zero" the visible range is on a linear wave-length scale. "Zero" wave-length would mean an infinitely high frequency: it does not exist.

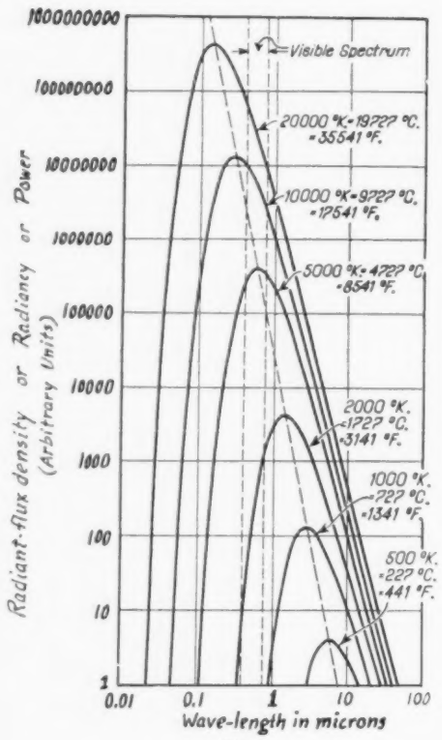


Fig. 6

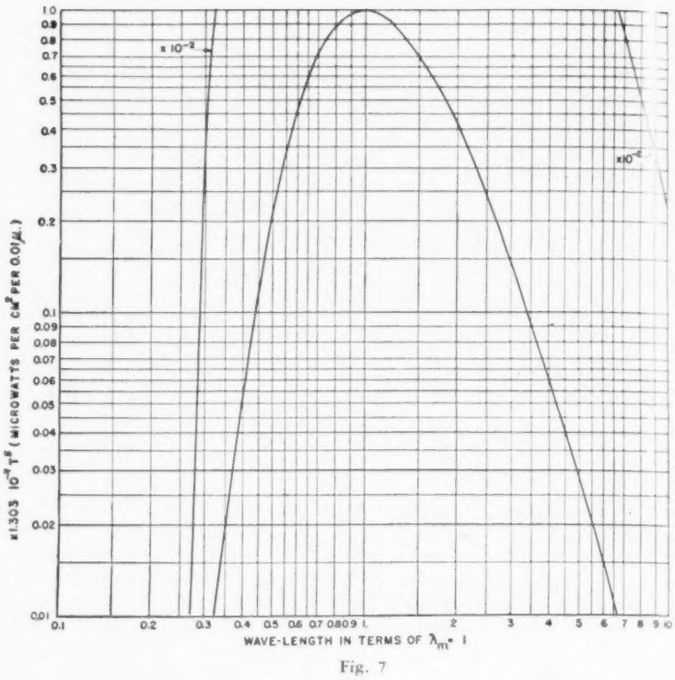


Fig. 7

THREE LOGARITHMIC-SCALE PORTRAITS OF RADIANT ENERGY'S BLACKBODY DISTRIBUTION AND POWER

The Fig. 6 diagram is from Sosman's "Pyrometry of Solids and Surfaces," but the legends have been re-lettered to create a certain effect. Note the shift of the peak toward the shorter wave-lengths as the temperature rises.

Fig. 7 is reproduced intact from a paper by Frank Benford (of G-E) in the *Journal of Applied Physics*. It is exactly the same general portrait as Fig. 4 but plotted on log-log coordinates.

Fig. 8 answers the question, how *powerful* is the radiation from a body obeying the blackbody laws? Note that by roughly converting from Metric to engineering units we get about a horsepower per square inch at about 4000°F.

hole will be a perfect emitter and perfect receiver of thermal radiations of all wave-lengths. Thus we can associate the blackbody and radiation in a more intimate way. The radiation laws become purified, so to speak. Good-bye gross matter!

The principal laws need not be altered but their interpretation is modified, as we shall see. The Bureau of Standards' statement that "total" radiation is "zero to infinity" is only of academic interest when we kiss matter good-bye, for that statement referred to "the total radiant energy of a material."

Yes, there are ifs and buts—and their consideration clarifies the picture.

The basic radiation laws are given in Fig. 4 and not here in the text, so that this discussion may be non-mathematical. They stand intact. Yet we shall attempt to explain in a non-mathematical way how it has come about that total radiation does not mean the total spectrum. (Readers with no previous knowledge of pyrometry, however, might examine Figs. 1 to 7 before proceeding.)

Radiant energy is a shower of photons of various energies. If its spectral limits were, say, 1μ and 2μ, and if the photons were evenly distributed, its portrait would be a rectangle, with a base of conveniently-drawn length representing one micron, and a height representing the (uniform) number of photons per 0.1μ or 0.01μ or any other convenient interval. To make the portrait represent energy distribution, however, the top line of the rectangle would slant and the portrait would become a rhomboid, the height of the sides being proportional to the frequency or photon energy, or inversely proportional to the wave-length. Thus, following the usual convention of drawing the shorter wave-length at the left, the left side would be twice the height of the right side; and the area (representing energy) would be the base times half the sum of the sides.

The sharp limits and the uniform distribution being imaginary, we need not draw the quadrilateral portrait.

Still assuming sharp limits at 1μ and 2μ, but assuming uniform distribution of intensity, or spectral energy density, we again have a rectangle. This time it remains a rectangle whatever its height. Its height, and hence its area, will be proportional to the fourth power of the absolute temperature. Again, there is no need to include a diagram.

Right now, nevertheless, while still considering this imaginary quadrilateral portrait, is a good time to mention an important feature of the real portrait.

If the area of the portrait is to represent blackbody rate of emission of *energy*, it will vary as the *fourth* power of the absolute temperature; but if it is to represent blackbody rate of emission of *photons*, it will vary as the *third* power of the absolute temperature. Since the fourth-power law is a feature of the real portrait (Fig. 4) it follows that photon distribution is not uniform in the imaginary sharp-limit portrait. In other words, there are half as many photons at the left-hand end as there are at the right-hand end. Which is just another way of saying that it takes half as many photons of a given λ or ν to make up a given spectral intensity as it does for photons of twice the λ or half the ν. The first and second quadrilateral portraits are thus reconciled.

A third imaginary sharp-limit portrait:

This time, imagine that the rectangle as a whole shifts toward the higher frequencies or shorter wave-lengths of the spectrum of radiation as the temperature rises. Its area (total energy) obeys the fourth-power law, so that its height will shoot up. But the photons obey the third-power law and they become more energetic as they correspond to higher frequencies, so there will be fewer of them needed; and the base of the rectangle will become narrower and narrower, even on a logarithmic plot.

Get it?

Good! You can better appreciate the beauty of the radiant features of Lady Temperature, whose portrait is shown in Fig. 4. Some of her features are depicted in Figs. 3 and 5. The terms radiant energy and radiancy must have been

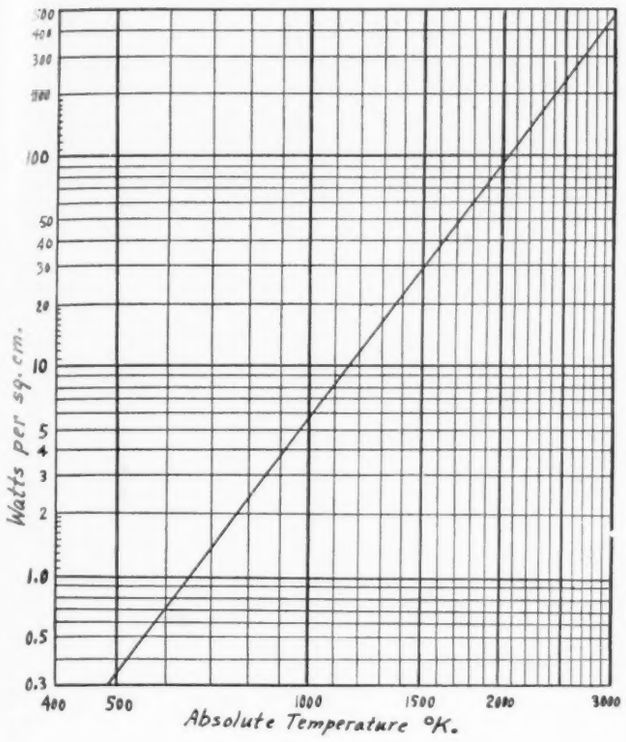


Fig. 8

coined by inspired geniuses! There is indeed a rare beauty in the progression of whole numbers we meet in the radiation laws and their corollaries.

Haas-Guth Law: Photon content varies as *third* power of temperature.

Stephan-Boltzmann Law: Radiancy or radiant energy density or power varies as *fourth* power of temperature.

Wien maximum-intensity corollary: Spectral energy at wave-length of maximum energy varies as *fifth* power of temperature. Knowing the temperature, $J_{\lambda m}$ may be found the simple relation:

$$J_{\lambda m} = 1.303 \sqrt[5]{\frac{T}{1000}}$$

Wien Displacement Law: Product of T and λ_m is a constant. The value of this constant (symbol b) is 2883.6.

Other interesting relations are brought out in Figs. 3 and 5.

The portrait of thermal energy is similar to that of visible energy (luminosity) in that both taper down to *nothing*. Mathematically, according to the wave theory, the curve extends to zero and infinity. But in 1915 (the very year that the Bureau of Standards issued *SP*250 on radiation pyrometry!) Einstein published one more paper on his photon theory of radiation, and this disclosure showed that the curves need not be prolonged to zero and infinity. In plain English, he showed that Nature sets a definite minimum in all interactions of radiation and matter — a "threshold" sometimes enormously larger than the tiny constant h which Planck had introduced in 1900 in his modification of the Wien laws. You may remember from Chapter I that there was a fascinating race at the turn of the century to formulate a valid law of radiation, that Planck won it in 1900 by proposing but not deriving a valid law, and that Einstein's discoveries in 1916 and 1917 finally "certified" the Planck law. The story is too complicated to narrate, for it began in 1905 when young and unknown Einstein first insisted, against Planck's own arguments, that Planck's quanta were not mere mathematical conveniences but *realities*. As D'Abro puts it "The real revolutionary was not Planck but Einstein." What is of interest to us here is that Einstein gave practical radiation pyrometry a boost — in fact, several boosts. In the first place, the radiation laws previously formulated by trial-and-error, follow naturally from his photon laws, in some cases in more accurate forms. In the second place radiation pyrometry can start from relations which do not involve *materials*. In the third place, the pyrometry of actual materials is *thereby* made more accurate, just as the Carnot-Kelvin ideal body made accurate "contact thermometry" possible. In the fourth place, the limits of all such curves of Nature as that of luminosity, radiant energy, etc., are given definite limits. We repeat, however, that the basic radiation laws which give the true portrait of radiant energy temperatures stand unshaken. (Overthrown, of course, are the original detailed formulations, such as Wien's of 1896.)

In Figs. 6 to 8 are given three more visualizations of the radiation laws, the originals having been selected from authoritative works. They are worth studying.

Mathematical readers will find *eighteen* "classic" radiation laws and *eighteen* photon laws in Worthing's recent but already historic paper.*

3. Sources—Effects of Materials and Surfaces.

In Section 2 the portrait of radiation temperature was painted in its true form. In spite of the mediocre artistry, it is hoped that readers caught a glimpse of the beauty of the subject. In an industrial plant, however, radiation temperature is like a veiled Venus, the reasons being as follows: (1) actual *materials* don't radiate perfectly; (2) *media* intervene between the material sources and the instruments; (3) the *instruments* themselves are imperfect because they are not like the ideal shown in Fig. 1 but are made of actual substances.

In this section we shall deal mostly with materials—particularly with their surfaces; and of course we shall use the blackbody as the reference standard.

Enclosures and Cavities

Before taking up materials and surfaces, it may be well to consider the possibility of nullifying most of their effects in actual industrial practice. Can the ideals brought out in Sections 1 and 2 be approximated, so that the imperfections of gross matter will not give serious trouble?

Since the most essential condition (see Figs. 1 and 2) is a blackbody source, every effort should be made to approximate it. Although this ideal is impracticable of attainment when the problem is to measure the temperature of a surface in the open, it can sometimes be closely approximated when kiln or furnace temperatures are to be measured. As far back as 1859, Kirchhoff pointed out that a *uniform-temperature* enclosure emits radiation through a small hole as would his theoretical "total radiator."

Moreover, there is an easy, familiar and generally reliable method of determining—literally at a glance—the closeness to blackbody conditions: If, when viewing a number of objects in the furnace, the *outlines* of these objects are invisible, measurements of the radiation will truly represent the temperature. It is to be borne in mind that the value of this simple test depends on there being on the furnace floor two or more objects *which have widely different emittances and reflectances in the open not only at room temperature but at red heats.* (The "emittance" and reflectance" properties are defined below.) Only then can the observer be fairly certain that equilibrium conditions prevail in the enclosure. We have to say "fairly" certain because the eye as a testing instrument can only check up on a small portion of the spectral distribution curve emitted by the enclosure. Below bright red, for example, the visible radiation constitutes less than 1% of the radiant energy to which the pyrometer should respond. Then, too, the objects selected for the visual test may have been selected by eye. Although they may have had enormously different reflectances in the open and at room temperature (black and mirror in appearance) and although they may have had distinctly different luminous

*A. G. Worthing, "Radiation Laws Describing the Emission of Photons by Black Bodies," *Journal Optical Society of America*, Vol. 19, Feb. 1939, pages 97-100.

emittance properties in the open when heated, they may still be unsuitable because even if their outlines merge as viewed by eye, there might not be complete equilibrium as viewed by the "eye" of a total receiver.

At dull red heats, these differences between an actual and an ideal enclosure as sources are serious. The higher the temperature, however, the less serious they are, for three reasons: (1) more of the energy radiated by the source lies in the visible, so that the value of the eye as a testing instrument is enhanced; (2) the emittance properties of many actual materials go up; (3) the fourth-power relation makes smaller the temperature-measurement errors due to nonblackbody conditions. Therefore, such enclosures as ferrous-

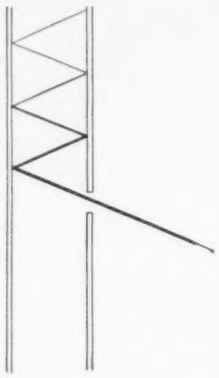


Fig. 9. Worthing's tubular blackbody: note how radiation through a small hole in the wall of a uniformly heated tube builds up to form blackbody radiation.

materials melting furnaces (2000 to 3000°F.) make excellent sources, provided only that the obvious geometrical requirements (Section 5) are met. The same applies of course to high-temperature bench furnaces and to most industrial high-temperature measurement problems where it is possible to view the inside of an enclosure through a relatively small hole—provided, again, that the image-size and other such factors are correct.

Dust, smoke, etc., in the enclosure, especially when *variable*, cause serious errors. No need to dwell upon this topic, except as it suggests the next-best solution of the source problem:—

Next to eliminating the effects of imperfections of material radiators, the *closed-end tube* offers a satisfactory solution of the source problem because its radiating properties remain constant (with proper care). The industrial plant differs from the research laboratory in that true temperatures seldom need to be ascertained. Therefore, although the sighting tube is made of a material, it is *one* material and makes an excellent source for industrial measurements. It is suitable for use not only in furnace walls but in molten metals, which are among the worst sources. The tube is more than a source: it really is an essential part of the pyrometer; and as such it will again be taken up in Section 5.

When neither an enclosure nor a closed-end tube can be used as a source, it sometimes is possible to take advantage of a *deep cavity* in a casting or other object whose temperature is to be measured. Such opportunities for the use of radiation pyrometers seldom occur, for the dimensions of the cavity must be at least as large as those of the closed-end tube specified for a particular radiation pyrometer. Small deep cavities offer good opportunities for minimizing nonblackbody errors when a telescope type optical pyrometer can be used; therefore this subject will be discussed in Chapter XI.

Importance of Distinguishing Between a Type of Material and an Actual Specimen and Surface

How many portable radiation pyrometers have been hurled in anger on concrete floors because their readings differed by more than a hundred degrees from those of optical pyrometers sighted at the same time on the same surfaces in the open? The author knows of two in the last twelve years. In each case the hurler later justified his condemnation of the instrument by pointing to a single-line entry in a brief table in an authoritative handbook: "It says here that the emissivity is 0.452. Three decimals, mind you! Then I 'phoned the lab and all the tables they looked up gave 0.43 and 0.47 as the limits." Or words to that effect . . .

Look up the "emissivity" of, say, "copper" in several general-reference handbooks. You probably will have to look for "emissive power," "emission factor," or other terms. Note the absence of footnotes or other ifs and buts in the condensed tables.

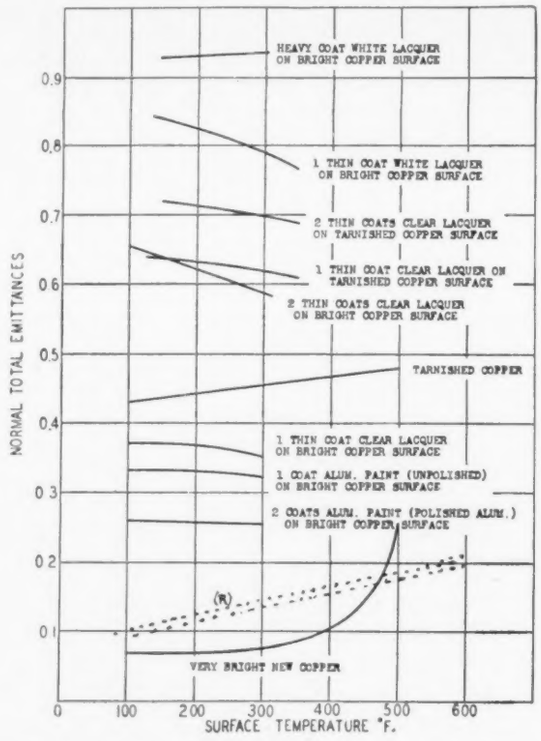


Fig. 10. (Heilman, *Trans. Am. Inst. Chem. Eng.*, Vol. 31, 1934, page 165; plus additional material: Worthing, *Jl. Applied Phys.*, Vol. 11, 1940, page 436) plus dotted lines showing electrical resistivities as explained in text.

Now examine Fig. 10.

No, don't draw your own conclusions yet — unless you have specialized in this kind of work. And even some of the highest authorities disagreed from the dawn of industrial pyrometry three-quarters of a century ago up to the late thirties. Or, rather, they *seemed* to disagree, because the concepts were not yet fixed and the workers in different institutions could not speak a common language. No wonder the portable radiation pyrometer was considered an inaccurate instrument! To use it successfully, one must first become acquainted with the radiation properties of materials and with the radiation characteristics of surfaces of actual bodies. These properties and characteristics are numerous. Only a few experts can recite all their names and definitions by heart. But remember what was said at the beginning of this chapter, that radiation pyrometry has been founded on the simple radiation laws and on organized knowledge of the complex effects found in practice. Once the reader has become even slightly familiar with the following discussion and list,* he can forget many of the exact wordings, for he will have gained a precious and permanent keneral knowledge of how to use his instruments even under unfavorable conditions.

*From the Temperature Symposium paper, "Temperature Radiation Emissivities and Emittances" by A. G. Worthing (*Journal of Applied Physics*, June 1940, pages 421-437.)

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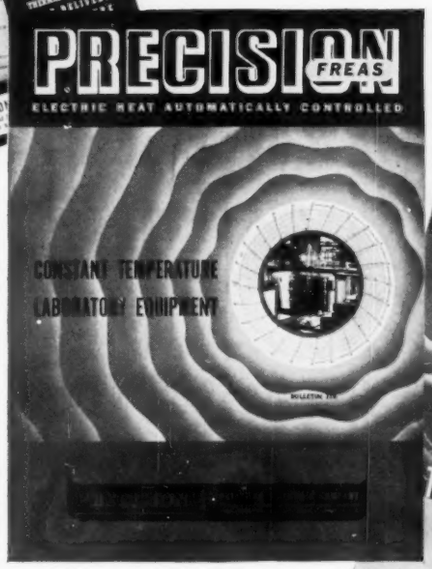

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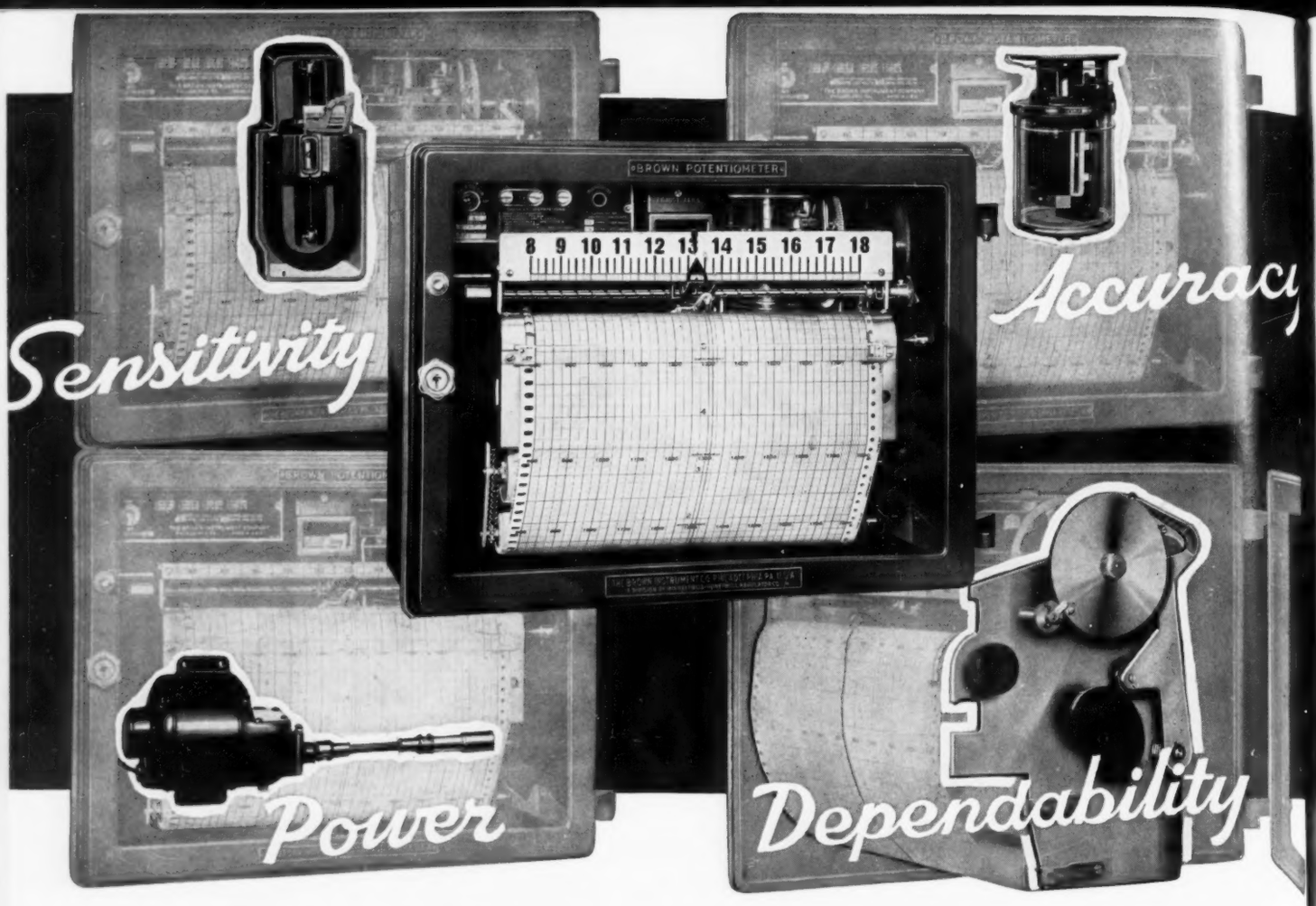

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Let us start with a familiar analogy:

The electrical "volume resistivity" of pure annealed copper is a definite property of a definite material; it has a known meaning whether expressed in microhms per cm.^{2} area per cm. length or (as among practical electricians) in ohms per cir.mil-ft. Also, the resistivities of pure annealed copper and of hard-drawn commercial copper are generally known to be different. But no one would speak of the resistivity of a mile of No. 18 copper wire: the *individual* characteristic of that particular "body" made of drawn commercial copper is universally known as its resistance. Likewise, in laying out a circuit where parts of it are near heat sources, allowance is universally made for the increased resistance of the heated copper conductors.

And yet the same type of careful workers, when using radiation pyrometers, will (sometimes through no fault of their own) overlook these important distinctions. Fig. 10 declares eloquently that there is a difference between the (normal total) emissi*vity* of copper as determined under standard conditions (clean polished surface, etc.) and the normal total emitt*ances* of the surfaces of various actual objects made of copper. Fig. 10 reveals also that the emissivity of copper varies more with temperature than do the resistances of copper conductors (dotted lines), and that the spread of emittances of actual bare and lacquered copper surfaces is far greater than the greatest spread between conductivities of different coppers (spread between dotted lines).

In addition to these effects, the emissivity of the clean polished surface of any pure material varies according to the spectral region—sometimes enormously; hence the term *spectral* emissivity (though many writers prefer "color emissivity"); and the spectral emittances of the actual surfaces of actual bodies made of those pure materials vary enormously and erratically.

Hence the distinction between *total* and spectral emissivity of a material; also between total and spectral emittances of actual surfaces.

Without qualification, "emissivity," whether total or spectral, conveys the general idea of rays shooting out at right angles from a surface. Therefore it is further necessary to distinguish between *normal* and *hemispherical* emissivities, for these two properties never have exactly the same value for any material: only the blackbody obeys the cosine law. When the temperature measurement problem is such that the surface must be viewed at an acute angle, it becomes necessary to apply two emittance corrections: that for the emittance of the individual surface and another correction taken from the curve of *relative* emissivity of the material for the angle in question—provided of course that the surface of the individual body is polished or at least clean and "smooth."

Obviously, a corrugated or serrated surface is a special problem in itself: it will have almost normal emittance when viewed from a point so situated that the greater portion of each ridge is normal to the line of sight; or—putting it in a different way—its hemispherical emittance will be a meaningless value because of the pseudo-polarization. Some machined surfaces are extremely tricky.

The emittances of irregularly rough surfaces differ erratically and unpredictably from the emissivities of the material. Consider for example a honeycomb, or any other "surface" which is about 90% deep holes and 10% outer surface: the composite will have emittance properties close to unity (blackbody), even if the material has a low emissivity and if the outer surface is highly polished.

Thus it becomes obvious that in the great majority of cases, an emittance (total or spectral; normal, hemispherical or for a specified angle) of an individual surface is *greater than the corresponding type of emissivity of the material.*

Emissivities and emittances are expressed as ratios, with the blackbody as the standard. For the blackbody, all values are unity, those of materials and of individual surfaces being written as 0. followed by one, two or three digits for the emissivities (one decimal place is close enough for many emittances!). Some texts and reference books, however, give emissivities as percentages. It makes no difference.

All absorption properties of the blackbody are likewise unity or 100% and the "coefficients" or "factors" of nonblackbodies (all defined in the abstract from Worthing's paper below) are similarly reported as decimals or percentages. In most cases these correspond to the emissivities of the materials listed in the tables, for the temperatures given. When temperatures are not given, not only will emittances differ from emissivities but emissivities will differ from absorptivities. All such tables, therefore, must be used with keen discrimination.

There follows now the list abstracted from Dr. Worthing's paper:

The emissivity of a material is defined as the ratio of a rate of emission of radiant energy by an opaque body with polished surface composed of that material as a consequence of its temperature only, to the corresponding rate for a blackbody at the same temperature. Thus a rate of emission of radiant energy per unit area by tungsten at 2000°K. is 23.7 watts/cm.^{2}, the corresponding rate for a blackbody is 91.8 watts/cm.^{2}, and the total hemispherical emissivity of tungsten at 2000°K. is 0.258. The several types of emissivity are defined below.

An emittance for a body at some constant temperature is defined as the ratio of a rate of emission of radiant energy by the body in consequence of its temperature only to the corresponding rate for a blackbody at the same temperature. The condition of the surface of the body, polished or not, oxidized or not, and the condition as to opaqueness are immaterial. For a tungsten filament at 2000°K. whose surface has been roughened greatly a hemispherical total emittance of 0.5 in contrast with the corresponding emissivity of 0.258 is not impossible. If the body is opaque the emittance has the emissivity as its lowest limiting value. For a glass rod at 1000°K., however, due to its nonopaqueness, one expects emittances less than the emissivities. In place of a normal spectral emissivity for visible light of about 0.96, one may obtain a corresponding emittance of say 0.10. Often the emittances of composite bodies, as of a shellacked piece of steel, are of interest. Their probable values range from zero to unity.

In giving precise definitions for the various emissivities, we need, in describing radiation sources, to make use of three well-recognized terms and a fourth which is not well recognized. They are* radiancy, steradiancy, brightness, and "luminous radiancy."

The radiancy of a source of radiation is its rate of emission of radiant energy per unit of area. It is commonly expressed in watts/cm.^{2}.

The steradiancy of an element of a source of radiation in a given direction is its rate of emission of radiant energy in that direction per unit area and unit solid angle. It is commonly measured in watts/(cm.^{2} steradian).

The brightness of an element of a source of radiation in a given direction is its rate of emission of light in that direction per unit area and unit solid angle. It is analogous to steradiancy and is commonly expressed in lumens/(cm.^{2} steradian) or in candles/cm.^{2}.

The "luminous radiancy" of a source of light is its rate of emission of light per unit of area. It is analogous to radiancy and is expressed in lumens/cm.^{2}.

We are now ready to give precise definitions for the various emissivities, each of which is defined for an element of polished surface of an opaque body at constant temperature.

A *hemispherical total emissivity*, $\epsilon_{h\,t}$, for the polished surface of an opaque portion of material at constant temperature, is the ratio of its radiancy to that of blackbody material at the same temperature.

A *normal total emissivity*, $\epsilon_{n\,t}$, for the polished surface of an opaque portion of material at constant temperature, is the ratio of its normal steradiancy to that of blackbody material at the same temperature.

A *hemispherical spectral emissivity*, $\epsilon_{h\,\lambda}$, for the polished surface of an opaque portion of material at constant tem-

*"Terms Used in Radiation Measurements." (Brief preliminary report of an informal meeting held at the National Bureau of Standards.) *Review of Scientific Instruments*, Vol. 7, 1936, page 322. See also W. E. Forsythe, *loc. cit.*

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perature, is the ratio of its spectral radiancy to that of blackbody material at the same temperature.

A *normal spectral emissivity*, $\epsilon_{n\lambda}$, for the polished surface of an opaque portion of material at constant temperature is the ratio of its normal spectral steradiancy to that of blackbody material at the same temperature.

A *hemispherical luminous emissivity*, ϵ_{hl}, for the polished surface of an opaque portion of material at constant temperature, is the ratio of its "luminous radiancy" to that of blackbody material at the same temperature.

A *normal luminous emissivity*, ϵ_{nl}, for the polished surface of an opaque portion of material at constant temperature, is the ratio of its normal brightness to that of a blackbody material at the same temperature.

A *hemispherical color emissivity*, ϵ_{hc}, for the polished surface of an opaque portion of material at constant temperature, is the ratio of its "luminous radiancy" to that of blackbody material having the same color as viewed visually.

A *normal color emissivity*, ϵ_{nc}, for the polished surface of an opaque portion of material at constant temperature, is the ratio of its normal brightness to that of blackbody material having the same color as viewed visually.

In use there has been considerable confusion due to a failure to distinguish between hemispherical and normal emissivities. This has been particularly true of total emissivities.

Emissivities, both spectral and total, vary with the emission angle. The definitions for the various types belonging to this group are obvious. They may be designated by $\epsilon_{\theta\lambda}$, $\epsilon_{\theta t}$, $\epsilon_{\theta e}$, and $\epsilon_{\theta c}$.

Types of emittances are equal in number to the types of emissivities, and we properly speak of the hemispherical total emittance of a body and of its normal spectral emittance. Emittances will be distinguished by primes, thus ϵ_{nt}', ϵ_{ht}', $\epsilon_{h\lambda}'$, etc.

Closely connected with the terms emissivity and emittance, in theory and practice, are the terms reflectivity and reflectance, and absorptivity and absorptance.

A *reflectivity* is defined for an opaque, polished portion of material as the ratio of a rate of reflection of radiant energy from its surface to the corresponding rate of incidence of radiant energy upon it.

An *absorptivity* is defined for an opaque polished portion of material as the ratio of a rate of absorption of radiant energy by it to the corresponding rate of incidence of radiant energy upon it.

Since all of the radiant energy which is incident on an opaque element of surface is necessarily either absorbed or reflected, the sum of a reflectivity and its corresponding absorptivity is necessarily unity.

As with emissivity, we speak of spectral and total, normal and hemispherical reflectivities and absorptivities.

For an opaque-walled cavity which has a uniform temperature throughout and is therefore in equilibrium, it is easy to show that a body in the interior is emitting radiation from its surface at just the rate that it is absorbing radiation from the walls which is incident on its surface. Not only is this true for total hemispherical rates of emission and absorption, but it is also true for the normal and the spectral rates for the conditions described, generally known as blackbody conditions. We may therefore write

$$(\epsilon = a = 1 - r)_T, \qquad (1)$$

the subscript T at the right indicating that not only the ϵ, the a, and the r are for the temperature T, but that the incident radiations also are such as occur in a blackbody cavity at the temperature T. The equation then holds separately for each type of ϵ, a and r.

If, however, the incident radiation has a spectral distribution different from that characteristic of a blackbody at the temperature of the element of surface in question, the simple relations given in the equation no longer hold for the total emissivities. The corresponding spectral values for ϵ, a and r are, however, as one will perceive, independent of spectral distributions and are therefore completely interrelated at all times by Eq. (1) as shown. To illustrate, for tungsten at 2000°K., $\epsilon_{n\lambda}$ at 0.665μ is 0.435 and the cor-

r ponding absorptivity and reflectivity values are 0.435 a 0.565. The value of $\epsilon_{\lambda t}$ for the same temperature is 0 60, but what the values of $a_{\lambda t}$ and $r_{\lambda t}$ are cannot be s ted unless the spectral distribution of the incident radiat n is known. If it is that of blackbody radiation corre- nding to 2000°K., $a_{\lambda t}$ and $r_{\lambda t}$ are 0.260 and 0.740.

(Dr. Worthing's paper then gives, in profuse details, methods of measurement and tabulated results, also discussions of results. He gives 52 references.)

Conclusion: We repeat that Dr. Worthing's definitions need not be memorized by practical pyrometer users in industry, but that their lessons should be kept in mind. Now here is exactly what to shoot at: No matter how different from the blackbody a surface may be, observance of the above principles of discrimination will make it possible to obtain *a straight-line relation between true temperatures and observed temperatures.*

P.S. What, no mention of the "graybody" in a discussion of sources? The graybody is one whose spectral emissivities are less than unity and have the same value at all wavelengths, so that the portrait of its radiation is a facsimile of radiation temperature's portrait, shifted toward the left. "There ain't no such animal" in radiation pyrometry: our nonblackbody sources are "colored" sources. In optical pyrometry, however, the concept of the graybody is sometimes heuristic.

4. Effects of Atmosphere and Other Intervening Media

In the shade of an old apple tree a boy sits reading a boy's encyclopaedia where, under the title of Rainbow, there is printed in natural colors a reproduction of the solar spectrum on a black background.

A storm cloud passes in front of the sun. In its shadow, the boy can still see all the colors, as he did in the shade—though he finds it a little harder to locate the exact places where the red and violet ends taper off into the black.*

The cloud goes by. All colors resume their respective brightnesses.

The boy puts on a pair of those new sun-glasses which, his dad said, highway safety directors recommend because they don't alter the colors of traffic lights. The effect is like that of the shadow of the cloud. Now the boy really understands what daddy meant by "scientifically gray."

A *Gray Medium* is one that reduces all spectral intensities in equal proportion. There are no truly gray media in Nature. The gray effect is realized by rotating-sector ("flicker") devices or by diaphragms or by opaque-mesh screens, but these are not media. For the visual range it is easy to approximate a perfect gray medium by polarization devices. For the total spectrum of radiant energy it is practically impossible. Every one of the 300-odd kinds of atoms of the elements and isotopes, every one of the hundreds of thousands of kinds of molecules, *each* of them makes love to only a few sizes of photons. Only in the ideal case, that of no medium between source and receiver (Fig. 1), does the entire spectrum of the source fall upon the receiver. Every total-radiation pyrometer is to some extent a selective-radiation pyrometer in actual use, but this in itself need not cause errors in temperature measurement.

The sharp cutoffs in the ultraviolet and in the infrared of the radiation from the sun and stars being known to every high-school graduate, the impression has grown that ordinary atmosphere errors greatly diminish the usefulness of radiation pyrometers. This is not the case. *Furnace* atmospheres are the offenders—not clean air at the usual source-to-pyrometer distances of several feet or yards. Even in the medium-humidity climates of American industrial centers, the usefulness of the radiation pyrometer, as a type of temperature measuring instrument, is not greatly diminished thereby. Complete allowance can be made for the cut-off of infrared by CO, CO_2 and water vapor, and for

*He will find it much harder, and the spectrum will seem narrower by at least 0.05μ at each end, if the printed "plate" faithfully reproduces the solar spectra which some observatories let visitors admire on sunny days.

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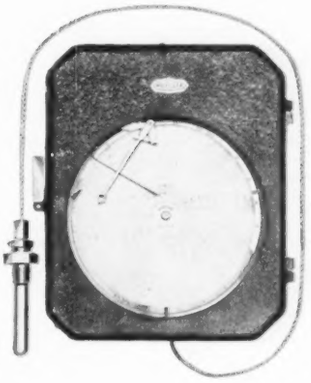

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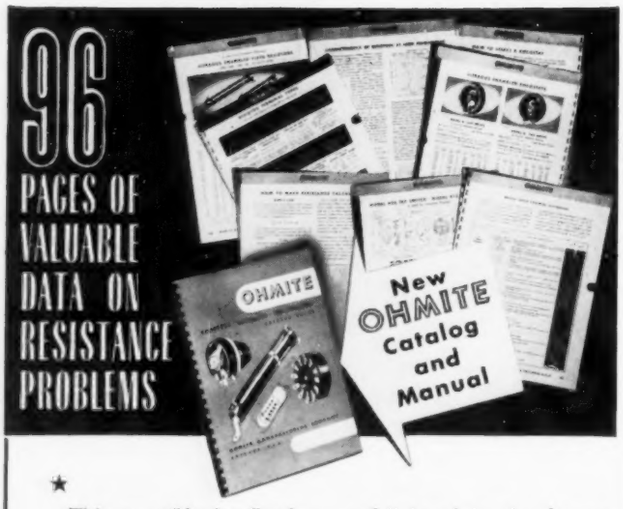

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the gray-medium effect of solid particles, under the following conditions:

(1) The *proportions* of absorbing gases, vapors, dust, etc., in the atmosphere between source and receiver must all be *constant*.

(2) The *distance* between source and receiver must likewise be *constant*.

These two conditions are interdependent. If any one of the various proportions of absorbing gases, smoke and moisture in the atmosphere is exceptionally high, this particular proportion will probably be variable and the total atmospheric absorption will not be constant; and errors will be introduced.

Humidity being generally uncontrollable, it sets a limit to the distance even when the atmosphere is otherwise standard and clean. Where the humidity error tolerance is 1% of pyrometer scale range, for example, the extreme limit will be (theoretically) about a mile in a dry climate where the humidity varies between 0 and 5%, and somewhat under ten feet in a moist climate where humidity varies between 60% and fog (saturation).

This distance limit will in any case be a complicated exponentional function by reason of the Bouguer-Lambert law of absorption, plus modifications for "haze" which seems to require putting both the distance and the particle-concentration in the exponent, as in Beer's law.

Excessive dust causes other errors which will be discussed later.

Flames. When any combustion process goes on in a furnace or kiln atmosphere, such atmosphere absorbs *more* of the radiant flux from objects sighted through it.

Glass, etc. Lenses and windows as parts of the pyrometer will be dealt with in Section 5. Here we consider the effects of interposing such media between the source and the pyrometer. Most media transparent to light cut off in the ultraviolet—which fact alone matters little, for it only requires, in the calibration, a slight departure from the fourth-power relation at temperatures above 3000°F. or thereabouts. They cut off a large portion of the infrared—and this greatly alters the calibration curve for temperatures below 1500°F. or thereabouts. In any case, however, the interposition of even a thin mica window to keep out dust will affect the *entire* calibration curve. Different glasses have greatly different transmission curves, but no need to dwell on this, for these curves show extremely small aging effects. In other words, the characteristics of fused silica, glasses, micas, etc., with regard to transmission of radiant energy remain constant throughout the life of the window unless discoloration flaws develop.

The transmission curves of all light-transparent media change, however, with the temperature of the material—the window itself, as distinguished from the source temperature. Therefore, they should be kept at "fairly" constant temperatures: the variations should not exceed 100°F.

To summarize: The effect of a fairly non-selective medium, or of a number of media whose joint effect is fairly non-selective, is a "grayish" effect, reducing the area of the "portrait" without seriously altering its "features." Temperature remains the fourth-root of the area under the curve—the fourth-root of the *reduced* area. Selective absorption alters the $T_S^4 - T_R^4$ relation in raising the power from 4 to 4 and a small fraction (T^5 applies to the extreme of selection at the peak). Accuracy depends on constancy.

5. Instrument Principles and Types

At the beginning of this chapter it was stated that some eighteenth-century arrangements of a collecting-system-and-blackened-thermometer in front of a peep-hole could be made to work today. Having read this far, you could make them work, for now you know that—

> *the function of a "total-radiation" pyrometer is to measure a continuous sample of the radiant energy or power from the source, and to indicate or record the fourth root.*

—which knowledge of the true function of a radiation pyrometer is more helpful to the practical pyrometer user than memorizing the names of all parts.

When source and receiver are blackbodies; and when the source temperature is higher than say 800°F. and the instrument is at room temperature, the basic principle is simple: The net transfer of radiant energy between the source and the receiver is $(T_s^4 - T_R^4) \times P$ where P is an instrument constant which depends on the geometry, etc. Since the receiver intercepts the radiant flux from the source over a small solid angle, its temperature at equilibrium will be low enough for the T_s^4 term to be eliminated. Since the receiver absorbs the total spectrum, its temperature at equilibrium will thus be proportional to the fourth power of the source temperature. The receiver temperature is measured by any suitable thermometer, usually a thermocouple or thermopile. The emf. being proportional to the receiver temperature and hence to the fourth power of the source temperature, a fourth-root scale on the millivoltmeter or potentiometer will give direct readings of the source temperature.

So much for the familiar simplified statement of the basic operating principle—applying to a blackbody pyrometer sighted on a blackbody source. Later we shall come back to our functional definition and discuss a nonblackbody pyrometer from the functional viewpoint. Meanwhile, a word as to types.

Radiation pyrometers may be classified in various ways, the most obvious division being into (1) portable (2) permanently installed. A portable pyrometer *in use* is subject to the serious errors mentioned in Section 3 and to the intervening-medium errors mentioned in Section 4. In addition, it is subject *in use* to sources of error arising from its own variable temperature—which variability is due to its being a portable instrument. However, when this same portable instrument is correctly installed, properly sighted into a closed-end tube, and otherwise subjected to uniform conditions, it almost seems to become a different type of instrument. Therefore, the writer has proposed the following prime division:

1. Hand
2. Autometric and autographic

—which means that a pyrometer consisting as usual of a receiving tube and of an electrical instrument will be a "hand" pyrometer while being used as such, on different sources; and it will become an autometric or autographic pyrometer when properly installed—even though it be installed temporarily. Conversely, an autometric or autographic pyrometer will be converted into a hand pyrometer when its tube is removed from the bracket or other such device.

The important prefix "auto-" signifies that the measurement is truly automatic, for the source is a part of the inner area of the closed end of *one* refractory tube; and the intervening medium is presumably a negligible factor. Therefore the scale readings are trustworthy: the instrument does not require a set of emittance correction tables or charts.

By implication, then, the readings of a hand pyrometer are not trustworthy. This is no fault of the instrument, as was brought out in Sections 3 and 4.

The endings "-metric" and "-graphic" refer to indicators and recorders.

Note well that the closed-end refractory tube is an essential part of the autometric and autographic instruments. A recording radiation pyrometer whose radiation-receiving tube is permanently installed at the side of a conveyor where slabs or billets pass on their way from one mill stand to another, for example, may be called a "graphic" device, but hardly deserves the designation *auto*graphic, unless the emittance properties of the surfaces, and the atmosphere, are *known* to be constant. In such cases only are the *temperature* measurements automatic.

Another classification is into—

1. Self-contained pyrometers
2. Separate-instrument pyrometers

—which cuts across the dividing lines of various other classifications. For example, a self-contained pyrometer is an autometric pyrometer when attached to a bracket and properly sighted into a closed-end tube for which it has been calibrated. Also, a separate-instrument pyrometer out-

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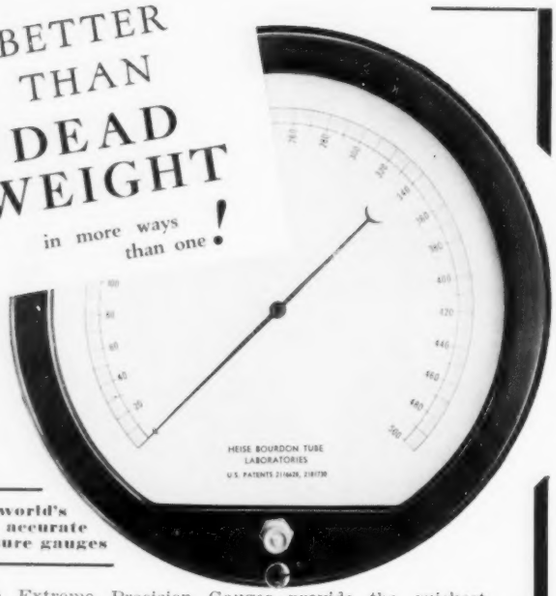

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fit may be provided with a shoulder strap and otherwise be truly portable. When not used with its closed-end tube it is a hand pyrometer.

Another important classification has to do with the type of energy-sampling system. This consists of the diaphragm, the focusing system, and the receiver proper. There are no "types" based on forms of diaphragms; but there are two classifications based on the radiation-collecting and -focusing systems. In Fig. 11 are shown the schematic diagrams of the five composite types. Note that there are two classifications, as follows:

I 1. Fixed-focus	II 1. Cone
2. Variable-focus	2. Mirror
	3. Lens

In practice the cone type is of the fixed-focus type; therefore there are not six composite types, but only five.

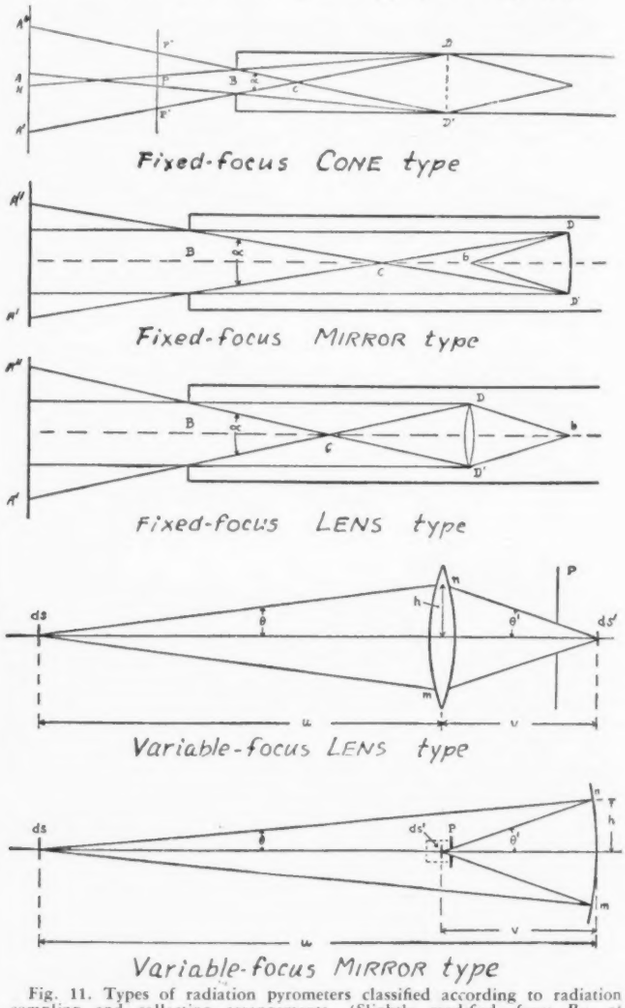

Fig. 11. Types of radiation pyrometers classified according to radiation sompling and collecting arrangements. (Slightly modified, from *Bu. of Stds. Sci. Paper No. 250.*)

Note that most of the radiation falling upon the receiver proper in the cone and mirror types is *reflected*. There is no such thing as a perfect reflector of all wave-lengths. Moreover, surfaces which appear to be nearly-perfect mirrors in the visible range are in most cases poor reflectors of infrared. On the other hand, surfaces which show a visible color may be better for use as radiant energy reflectors. Gold is the best of the readily-usable and serviceable materials: its alteration of the fourth-power relation is so small that the effect, according to the Bureau of Standards *Scientific Paper No. 250*, "does not become practically appreciable until above 2500°C." At higher temperatures, where more of the radiant energy is carried by higher-energy photons, the selectiveness of gold cuts down the total to such an extent that calibration departs from the fourth-power relation more and more widely—by about 300°F. at about

60 °F. For most industrial purposes, the reflecting types may be considered "graybody" receivers—not blackbodies but not definitely selective.

The same may be said of the lens types as industrial pyrometers; though, strictly speaking, the absorptivity of glasses and fused silica is selective—highly selective at source temperatures below red.

Focusing geometry of fixed-focus types, and the mechanical or optical fine points of variable-focus types, used to be the subject of endless arguments. That was back in the days when some ingenious-looking designs were botched in actual manufacture—in the days when such pyrometers were found by the Bureau of Standards to show errors of "hundreds of degrees." Those days were before the First World War; today this subject is mentioned because inexpert "monkeying" will cause errors just as huge.

Manufacturers have prepared instructive charts, etc., pertaining to correct focusing and related precautions. Some of the illustrations are reproduced in the next section.

The receiver proper, sometimes called the "sensitive element," may be of any form, but its radiation-receiving area should only be of one "color"—which is absence of color: dead black. A morphological classification of receivers is difficult because their form is governed by that of the primary element of the thermometric system. Thus the simplest combination of a receiver and thermometer is a tiny bimetallic spiral—in which case we might say that the receiver is its own thermometer (but the pointer and scale are essential parts of the thermo*meter*).

Although the receiver proper may assume a great diversity of forms, there is an obvious classification of the thermoelectric types into "open" and "glass-enclosed" or "bulb." These latter, in turn, may be divided into "vacuum" and "gas-filled," also into "glass" and "fused silica." By the same token we should divide the "open" types into those which are completely open to source radiation without intervening lenses or windows, and those which are embodied in receiving tubes of the lens type (or of the mirror type in which there is a window). Thus an "open" disk in a lens type tube (or in a windowed mirror type tube) will have certain characteristics in common with a disk in a gas-filled bulb at the focus of a windowless mirror type pyrometer tube. One of these common characteristics—convection as a cooling factor—will not be shared by the vacuum receiver, which is cooled by reradiation and conduction. But other details of the design and construction of the entire units determine the time characteristics. For example the glass bulb may be enclosed in a closely-fitting metal case (with a hole for the passage of the flux to the disk) in order to make the reradiation from the disk less dependent upon the temperature of the outer tube of the assembly. Thus the sub-types and varieties multiply themselves as these factors are taken into consideration. On the whole, therefore, it does not seem justifiable to speak of the "advantages" and "disadvantages" of such interlocked and interdependent types, sub-types and varieties—especially in view of the fact that some designs are modified every two or three years as advances are made in the lamp and vacuum-tube industries.

The next classification is according to the method of measuring the temperature of the receiver proper. A list of possible methods would coincide with most of the items in some of the tables given in Chapter II. In practice, however, the great majority of systems are thermoelectric.

Functional Analysis

The total-radiation pyrometer was purposely defined above as a radiant power sampling and measuring device—though not in these exact words. It is as such a device that it will now be briefly described and discussed. Only a few points will be touched.

The sampling is accomplished as follows: A diaphragm is used to obtain a definite area, hence radiant-flux density or radiancy, or *power*. This is an important first step in sampling. It suggests that the range may be changed by simply changing the area of the *prime diaphragm* or *entrance pupil*. A mirror or lens arrangement focuses this radiation upon a receiver whose area is smaller than that

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of the diaphragm, so as to multiply radiancy by the inverse ratio of areas (not an essential principle but obviously useful in practice).

The receiver proper is the next-best thing to a blackbody receiver, namely a blackened-surface device. For the moment we call it a *disk* (though its form is not a matter of basic principle). At the start, all (or say 99%) of the photons that fall upon the black surface become ordinary thermal-energy quanta; and the disk heats up. This erstwhile "cold" disk was of course obeying Prévost's law of exchanges: receiving and radiating photons in all directions—most actively to and from its blackened surface but at a slow rate. When face to face with the source, its temperature rises because of the continuous *net gain* of energy.

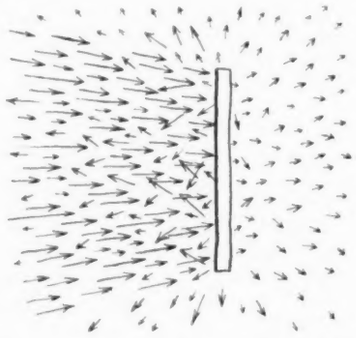


Fig. 12

Now (Fig. 12), it radiates in all directions at a faster rate, faster still from its blackened side, fastest of all in the direction of the source!* Equilibrium conditions are eventually established when the incoming and outgoing rates of emission become equal—the time from "cold" depending on the mass and specific heat of the receiver, upon the blackness of the surfaces surrounding it and upon how much colder these surfaces are. The receiver doesn't hang in empty space; it is supported. Therefore this time (called lag) is increased because the support has to be heated. Equilibrium is only reached when the convection-and-conduction-and-radiation outgo equals the net radiation input from the source. (No convection outgo in the case of the vacuum-bulb receivers.)

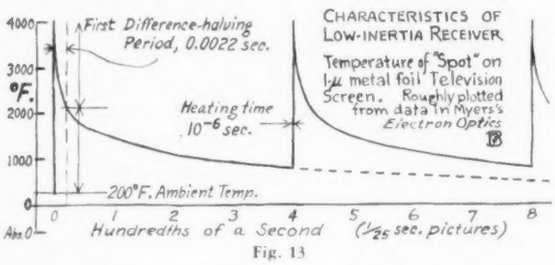


Fig. 13

What is the minimum possible lag? Discussions have raged for years—inconclusively because a minimum-inertia receiver consisting of a monatomic layer of a "black" element over a thermopile or bolometer several atoms thick is not practicable . . . yet! One possible answer seems to loom up in a rather unexpected field: television. See Fig. 13†.

*We assume normal incidence—the customary orientation.

†Pages 538 to 569 of Myers's "Electron Optics" (Van Nostrand, 1939) deal with "Temperature Screens" and this title would naturally attract the attention of any temperature instrumentician. It was particularly interesting to note that Dr. Myers has formulated several equations applying to television screens made of blackened *metallic* foil. Dr. Myers concludes that the materials and methods now available are not adequate and gives supporting data. The writer being curious to visualize the scanning-period temperature history of an element of area on a temperature screen, he plotted something like Fig. 13. Immediately, the radiation-receiver possibility became so evident that the writer then plotted Fig. 13. The relations shown do not apply to the supported edges of the screen, of course. The interesting part is not only the microsecond heating time (beam energy in the form of electrons, not photons) but the cooling time, because this provides a valuable clue to the value of the lag coefficient of a somewhat similar screen supported by filamentary leads. The decay curve, though not exactly logarithmic, suggests a roughly corresponding lag coefficient.

Another answer, in the evolution of cathode sputtering from a delicate art to almost a manufacturing process. Another, in the optics: larger entrance pupil and smaller image, decalling customary "power" (condensing or concentrating power in the sense of geometrical optics). Another, in the use of translucent coatings which "trap heat" as does ordinary window-glass in hotbeds. And so on . . . Pyrometer manufacturers have presumably been exploring these different roads to the ideal of inertialess receivers.

Strange to say, an inertialess receiver need not be a massless receiver. It can be thermally inertialess and yet be heavy. It may be described as one which instantaneously transforms all photons into electrons—which instantaneously transforms the watts of radiation into watts that can operate an electrical instrument. The ordinary photocell does this selectively (see next chapter, on optical pyrometers), hence inefficiently. The blackened thermocouple does this partly (reradiation losses), hence—likewise—inefficiently. At any rate, the usual method of measuring receiver temperature by a thermoelectric thermometer is more efficient than is any method permitting all of the radiant energy entering the pyrometer to heat up the pyrometer itself.

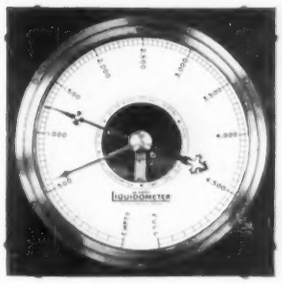
Which naturally leads to the topic of pyrometer temperature—the temperature of the receiving tube. Two distinct aspects of this question must be borne in mind by the users of radiation pyrometers:

(1) The temperature of the receiver proper is an equilibrium temperature, reached when input equals outgo. Variations in the temperature of the surfaces to which the receiver proper reradiates will change the value of each equilibrium temperature which is supposed to represent a definite source temperature. Years ago, some receiving tubes were so bad in this regard that they literally had to be handled with gloves. Today's portable pyrometers are better. Some of them have automatic compensators. But complete compensation would involve thermostating the entire tube. This is one of the reasons why we insist on the "hand" *vs.* "auto-" distinction. Even the best-made receiving tube is influenced by its surroundings. Surround it by a water jacket and you minimize serious sources of error.

(2) The foregoing was the *general* case. The special case of the thermoelectric method of measuring receiver temperature (though it is the usual case in practice) presents the special problem of reference-junction compensation. Section 7 of Chapter IX was entirely devoted to this subject. It need only be stated here that reference-junction compensation is much more important in radiation pyrometers than in thermoelectric pyrometers. How much more important? By the ratio of differences between hot and cold junction temperatures. In other words, when a measuring junction is at 2075°F. and its reference junction at 75°F., a 20° change in room temperature will cause an error of 1% in the emf., which will approximately correspond to a 20° error in the temperature reading if the range is not "suppressed." But when a temperature of 2075°F. is represented by a 20°F. *difference* between the measuring and reference junctions of a radiation pyrometer, a 20°F. change in room temperature will completely destroy accuracy.* Note however that the errors are not as great as some users seem to fear. We purposely emphasized the word *difference*, because gradual changes in room temperature, having equal effects on hot and cold junctions, are not so bad. What is to be guarded against is a sudden change. Some radiation pyrometers of the thermoelectric thermometer type embody automatic reference-junction compensation. Their tube error coefficient is thereby minimized—but not always completely eliminated. Here is why: A fairly gradual change of room temperature can be considered as a temperature wave which travels so slowly through the pyrometer that

*This 20°F. difference is true only at the low end of low ranges. The highest difference seldom exceeds hundreds of degrees; it never runs into the thousands, despite the frequently-heard (and once advertised) statement that the focusing is so powerful that the disk gets hotter than the source. The Second Law of Thermodynamics hasn't been repealed.

Accurate TANK GAUGES for Every STORED LIQUID



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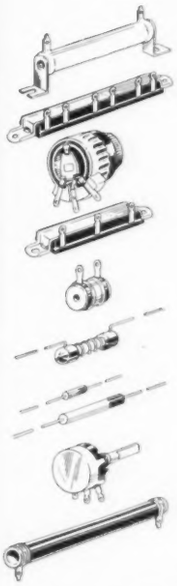

With dozens of resistor types available, it is often difficult, even for experienced engineers (who have many other things to think about) to choose the most economical and reliable unit. Cost, possible combinations, ease of assembly, mounting requirements, protection and many other factors must be considered. That is where IRC can be of help. Backed by the largest line of fixed and variable resistors made by any manufacturer, IRC specialists are in a unique position to help design and production engineers select the best, most economical unit for their particular job. It pays to ask IRC!

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the reference junction and the reference-junction compensator are at the same temperature; but in the event of a sudden change there will be an interval during which the R.J. and the R.J.Comp. will be at different temperatures. In actual practice, a portable pyrometer is usually subjected to the most rapid changes when it is taken from its box and used in a different environment—the sudden change then occurring at the time a measurement is taken!

"Watch out for the temperature waves" is another way of putting "watch out for temperature gradients"—the advice which Dr. Sosman of the U. S. Steel Corp. has been preaching to metallurgists with excellent results.

In radiation pyrometry, temperature wave errors are caused not only by changes of environment but by changes in the cycles of use. This applies in particular to the portable pyrometers. The effect is as follows: When a portable receiving tube is sighted upon a source, the establishment of equilibrium between the receiver proper and its surroundings is only temporary:—

(1) In the first place the heated disk or other receiver becomes a source. It starts a wave. The "reading lag" represents the time to reach a temporary equilibrium. Ultimate equilibrium is attained only at the end of a much longer time—in some cases five minutes to as long as an hour—during which there is a see-saw action (look up books on heat conduction, chemical engineering design, etc.) Nowadays, this is not troublesome, but there are in use some old pyrometer tubes of certain designs which, when tested by the Bureau of Standards, were found to oscillate slowly with amplitudes of 50°F. or more after reaching the first equilibrium in an apparently satisfactory way.

(2) In the second place, when a receiving tube of certain types is taken to the vicinity of a source such as a large forging, for example, the heat image defined by the diaphragm begins to lose its sharpness because of the edge effect, so that the receiver no longer "sees a hot circle surrounded by cold" but "a hot circle of increasing diameter, shading into outer cold." Moreover, the heated diaphragm, and the front parts in general, start a temperature wave from the front to the back of the receiving tube. Again it is a pleasure to report that the modern receiving tubes are better in this regard. Again it is necessary to mention the old tubes in use.

Only the beginning of the use cycle has been discussed in the two foregoing paragraphs. It is obvious that a portable radiation pyrometer, however excellent its design and construction, will give slightly different readings throughout a workday during which it is used (or abused) in such manner that its front end will be subjected to 200°F. alternations of hot and cold. If the use cycle frequency matches the natural period of the longitudinal temperature oscillation, the resonance will build up the error to such an extent that a good pyrometer may unjustifiably be condemned.

Stray Radiation. In addition to the more-or-less systematic or analyzable errors due to undesired radiation, mentioned in the foregoing discussion, there is sometimes the possibility of stray radiation falling upon the receiver. Modern designs make this a rather remote possibility, insofar as direct radiation is concerned. What is to be guarded against is reflection; also, in some instances of thin-walled housings, reradiation from local "hot spots."

Distance Factor. The geometry of receiving tubes is such that the readings should be independent of the distance from the radiating body, provided that the former be large enough. In general, it is simply necessary to limit the beam received at the pyrometer to a cone of constant apex angle. Then, provided that the base of this cone, or "circle of application," is completely filled, the reading will be independent of the distance.

This may be demonstrated by discussing the various types shown in Fig. 11. It can be made more evident, however, by referring to Fig. 14 which is a simplified diagram of the Thwing cone type radiation receiving tube.

No radiations reach the conical mirror from any part of the observed surface outside the solid angle AOA', and all radiations from the surface falling within this angle are transmitted by multiple reflection to the thermocouple at the

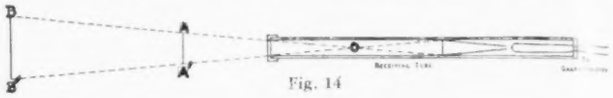


Fig. 14

small end of the cone. If, for instance, the energy E, received from a surface of area S at a distance OA be compared with the energy, E', received from the larger portion of the same surface S' subtended when the distance is $OB = 2OA$ it will be seen that:

$$E/E' = S/(OA)^2 \div 4S/(2\,OA)^2$$

or,

$$E = E'$$

since the area increases with the square of the distance and the intensity varies inversely with the square of the distance. Note again, however, that while the distance BB' may be varied, the source must always have sufficient area to fill the circular surface of which BB' is the diameter.

The diameter of this surface, with the Thwing instrument, should be 1″ for every 8″ of distance from the end of the tube for a low range (2500°F.) instrument and may be correspondingly smaller for instruments of higher range which have smaller diaphragms or windows.

This ratio (of 1″ to 8″) is known as the distance factor. Some writers express it as one to ten (or whatever); others simply as the second number.

In practice one may be sure that the safe distance is not being exceeded as long as increasing distance does not decrease the reading. The eye-sighted types, of course, simplify this determination.

6. Industrial Forms

The following does not aim to serve as a complete list of the modern American radiation pyrometers. In this regard it is incomplete. On the other hand, some foreign pyrometers in use in America are included.

In the following, the emphasis will be on radiation pyrometry—not on the characteristics of the indicating and recording electrical instruments. (See Chapter IX, Sections 8 and 9, for details on the millivoltmeters and potentiometers used in thermoelectric pyrometry.)

Therefore, whenever the *lag* is mentioned, the time in seconds refers to an inherent property of the radiation-receiving tube and not of any electrical instrument. In other words, the reading lag given is that for an outfit consisting of the receiver unit and a "typical" indicating millivoltmeter.

In some cases, the radiation-receiving tube or "head" or "unit" is made by company "A" and sold to the user by company "B". In other cases "A" makes and sells, and "B" sells, but "A" supplies "A" instruments while "B"" supplies "B" instruments, so that there is an "A" pyrometer and a "B" pyrometer which have the same tube. In still other cases the head made by "A" and the instrument made by "B" are installed by "C" with "C" installation parts as a "C" pyrometer pictured in the "C" catalog. And there are even more complicated cases. The following does not aim to be a commercial guide: only the most essential *identifying names* are mentioned.

* * *

Féry Pyrometer—The first "total" radiation pyrometer was devised by Féry in 1902. It consisted of a telescope, the object-glass of which focused the radiation from the source on a thermocouple connected to a galvanometer. A large proportion of the radiant flux from the source could not pass through the glass. In 1904 Féry met this objection by using a concave mirror.

The Féry pyrometer of today is manufactured in the U. S. by the Taylor Instrument Companies and in England by

t[illegible] Cambridge Instrument Co. which first brought it out. A[illegible] interesting feature is the method of focusing by means o[illegible] a small split mirror: the image of the source is viewed th[illegible]ough an eyepiece at the rear. The mirror is in two halves w[illegible]ich are out of alignment until the main collecting system i[illegible] focussed on the receiving disk—which is done manually by a[illegible] rack and pinion (Fig. 15).

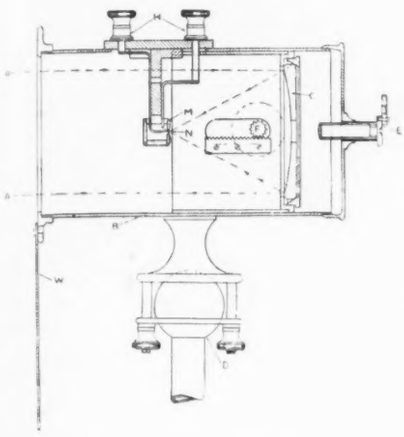


Fig. 15. Section of Féry Optical Pyrometer. AA — Beam with large diaphragm. C—Collecting mirror. E—Ocular for focusing image on disk. F—Focusing rack. M—Split mirror which shows image out of line when main collecting mirror is not properly focused. N—Receiving disk at hot junction. *(Cambridge Instrument Co.)*

Taylor Instrument Companies—A concave mirror concentrates the radiant flux on a receiving disk of copper $\frac{1}{16}$″ in diameter and 0.003″ in thickness located at the thermocouple junction. One thermocouple is used, made up in the form of a plus mark, or cross, with a receiving disk placed at the intersection of the thermocouple elements. The thermocouple material is iron-constantan ribbon. The available ranges are 1000 to 2400°F., 1500 to 3600°F.; 500 to 1300°C., 900 to 2000°C. The focus of the reflecting mirror is adjustable. The distance the telescope must be placed from the furnace is determined by the size of the object. An object 3″ in diameter can be read at a distance of 10 feet from the furnace. This gives a distance factor of 1 to 40. The lag to attain full-scale reading with each range is 3 to 5 seconds. Approximately 6 millivolts are developed at the top mark of each range. With the diaphragm open at 2400°F., or with the diaphragm closed at 3600°F., the temperature of the receiving disk at the thermocouple is approximately 210°F. The indicating instrument is of the vertical-coil type with a scale approximately 6⅝″ long.

Cambridge Instrument Co.—The Féry radiation pyrometer made by this firm is similar in its design. Some of the differences are that the collecting mirror is made of stainless steel; that two thermocouples are used, made of special thermoelements which develop from 4 to 12 millivolts at the high point of the scale, depending upon the range, and that the distance factor is 1 to 24. A sectional view is shown in Fig. 15.

Whipple-Féry Closed Tube Pyrometer—This is a modified form of the Féry mirror type radiation pyrometer. It consists of a long iron tube, closed at one end by a blind tube of fire-clay, carborundum, quartz or steel (to suit various requirements). The radiant flux from the closed end is reflected at the opposite end of the instrument assembly by the concave mirror, and brought to a focus at which is affixed a small thermocouple. A wide flange protects the hand of the observer from the heat in the case of open crucibles, etc.

Leeds & Northrup old (Foster) model. Also, *Foster Instrument Co.*—Many of these tubes are still in use; some are on the market. This is a fixed-focus receiver of the thermoelectric type. The tube can be held by hand but is designed chiefly for permanent installation. The distance factor is 1 to 10 for all standard receiving tubes except that to 1800°C. in which case it is 1 to 12. The radiant flux is concentrated on a thermocouple by a convex mirror at the end of the tube farthest away from the furnace. The mirror is mounted in a cell and sealed to prevent tampering. Users having technical skill may break the seal, remove the mirror cell, clean it and replace it. The emf. developed by the thermocouple when sighting an object at 1400°C. is 14 millivolts.

Leeds & Northrup Co. "Rayotube."—This company's new receiver is available at this writing in some forty to fifty combinations of tubes and various water jackets and closed-end refractory or metal tubes, including models for source temperatures as low as 225°F.; also "Narrow Angle" models for target diameters as small as 1″. No detailed

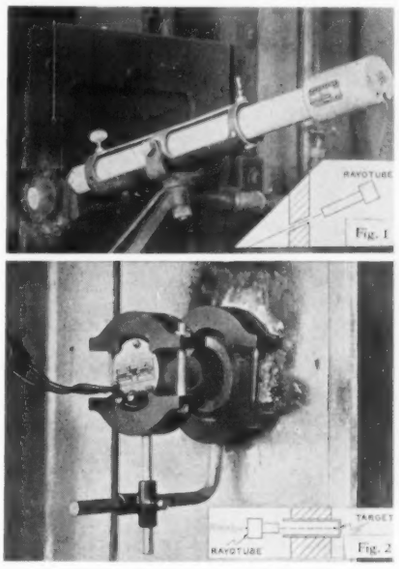


Fig. 16

sectional diagrams have been released by the manufacturer and it would seem that there are several distinct types of "Rayotubes" without taking the variety of appurtenances into account. Some are evidently of special low-lag design and construction, being suitable for use with the company's "Speedomax" recorder for recording the temperature gradients along the lengths of slabs, billets, rails, etc., being rolled—which probably is the "fastest" standard industrial application of radiation pyrometry.

Keiser & Schmidt. In this self-contained instrument (Fig. 17) the sensitive element is not a thermocouple but a bimetallic spiral about 1/10″ in diameter and 1/1000″ thick, placed at the focus of a collecting lens 1⅛″ in diameter with a 2″ focal length. This is a compact device—almost a pocket instrument. The method of compensation

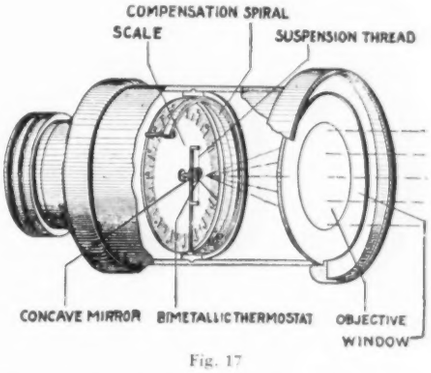


Fig. 17

for variation of room temperature is as follows: The scale over which the pointer travels is automatically shifted by a compensating spiral. This scale is transparent and can be seen at the same time the glowing source is viewed through the ocular, enlarged about 8 times. The distance factor is approximately 1 to 12. The instrument is 6″ long and 2″ in diameter, and weighs 6 ounces. The lag is said to be about 10 seconds.

"Pyro" (Pyrometer Instrument Co.) (1) Portable.—This is a 7″ long self-contained ("pocket") fixed-focus collecting-lens type instrument of German make (Dr. R. Hase). The receiving disk is in a vacuum bulb. One thermocouple is used. Distance factor, 1 to 15. Minimum diameter of source, 2″. The lag is said to be 2½ to 3 seconds. The construction of the instrument is interesting in that the galvanometer

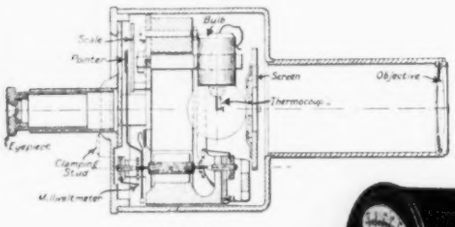


Fig. 18

Fig. 19

is built around the telescope so that no leads are necessary. It would seem that it takes a little practice to use this instrument properly. A feature of convenience is the button ("clamping stud" on diagram) which is pressed when the instrument has been sighted, and then released: the pointer remains fixed until again released by a second pressure of the button. Two models are available, each a double-range instrument: (1) 1000-18000 & 1800-2600°F., (2) 1400-2400 & 2400-3600°F. Each is of the fixed-focus type but with a sliding eyepiece to suit the user's eyesight.

(2) "Supersensitive."—This likewise is a telescope-sighted, fixed-focus lens, thermocouple-bulb receiver, but it is designed for higher temperatures, does not incorporate a millivoltmeter and is available in a water-jacketed housing.

The *"Ardometer"* Unit. *Bacharach Industrial Instrument Co.* (manufacturer); *The Bristol Co.*—This is a lens type receiving head with a glass-enclosed thermoelectric receiver proper. The unit (see Fig. 20) embodies a sighting telescope with an objective lens 1 and an ocular lens 3. Radiation is focused by the object lens on to a blackened platinum disk to which thermocouple wires are hard-soldered. A diaphragh between object lens and bulb determines the particular temperature range of the unit. In use, the telescope is sighted on the source. The observer looks through ocular 3, after he has suitably adjusted it to his own eye. In order to avoid dazzling the eye during adjustment, a small colored glass (4) may be inserted in front of the ocular lens. He also sees, in the center of his field of vision, the blackened receiving disk. The telescope is directed in such a manner that the brightest part of the surface of the hot body, or that part whose temperature is required, is nearly covered by the disk. The observer should now see a uniformly bright zone all around the circumference of the disk. Fig. 24 shows actual photographs of correct (top) and incorrect (middle) sighting of a small round source such as a furnace peephole, and an example (bottom) in which the source is insufficiently large as viewed, in which case the observer should come closer. (This applies to other telescope type units and will not be repeated.) Minimum source diameter, 1″ (½″ with special Ardometers). Distance factor, 1 to 11. Lag, 3 seconds for full deflection. This radiation receiving unit or "head" may be used as a "hand" pyrometer if the source diameter and other local conditions permit keeping within the distance factor. It may be attached to a tripod (supplied by Bacharach). However, both Bacharach and Bristol recommend that it be installed in a water-cooled housing. Each of these two firms supplies two types, "light" and "heavy-duty." Bacharach supplies millivoltmeter indicators (portable) and recorders (portable or switchboard). Bristol has a complete line of millivoltmeter and potentiometer indicators, recorders, controllers and combination instruments.

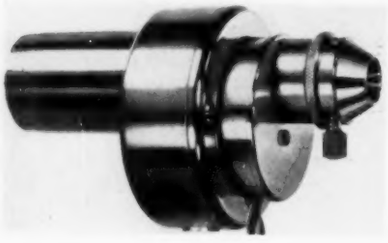


Fig. 20

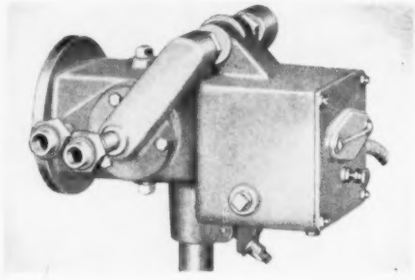
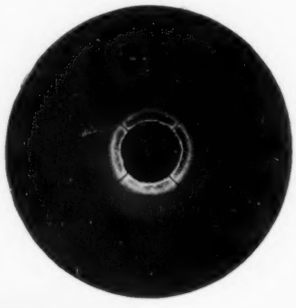


Fig. 21



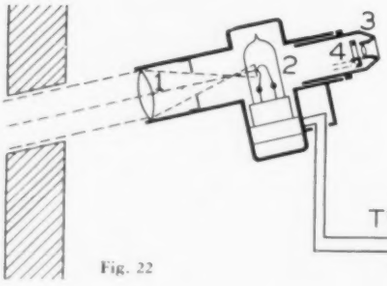
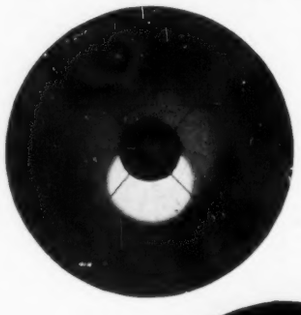
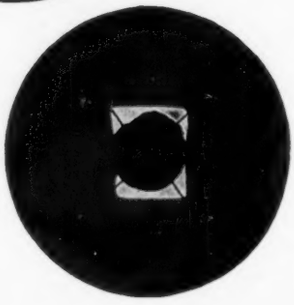


Fig. 22

The "Ardometer," Figs. 20 and 21 *Bacharach Industrial Instrument Co.*; Figs. 22 and 23 *The Bristol Co.*



Fog. 24. Correct (*top*) and incorrect sighting of telescope type radiation pyrometer. (*Bacharach Industrial Instrument Co.*)



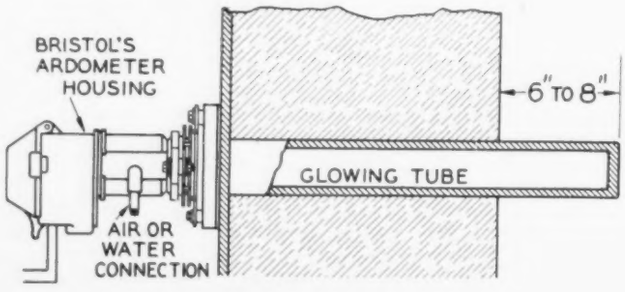


Fig. 23

Thwing-Albert Instrument Co. (1) Portable.—The construction of this receiving tube is shown in Fig. 25. It is of the "universal" or fixed-focus cone type. The radiant flux passes through a series of non-reflecting diaphragms and

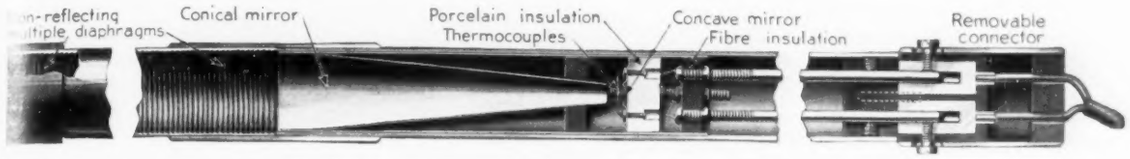


Fig. 25

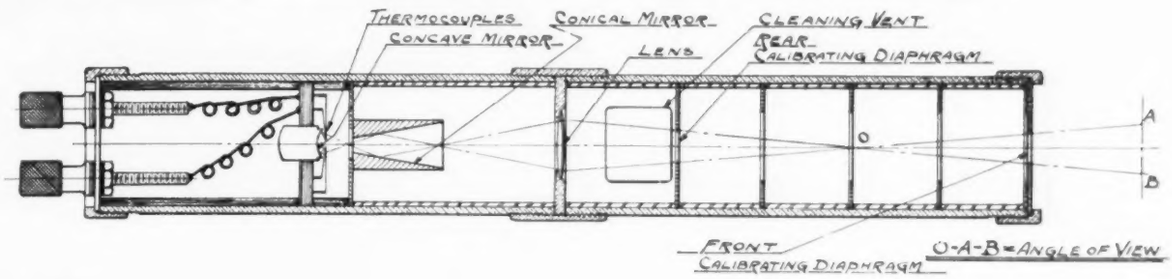


Fig. 26

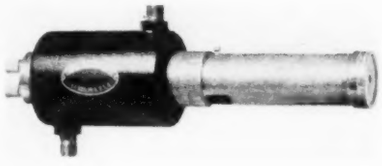


Fig. 27

falls on a conical mirror which reflects the rays back and forth until they finally are concentrated on a thermocouple. The outside diameter is 1" and the length 30". The construction is into two separable sections, for convenience in carrying. Six thermocouples are used, connected in series. The distance factor is 1 to 8. The time lag to attain full-scale reading is 15 seconds, and 7 to 10 millivolts are developed at the high point of each range. Thirteen single-scale and five double-scale portable millivoltmeters are available; seven single- and two double-scale wall-mounting models. The hot junction temperature is about 210°F. when the measured temperature is 3000°F. This portable tube must be held at the end; if grasped in the middle, a slight error is introduced. A fixture is provided by the manufacturer, whereby this portable tube can be permanently installed.

Twing-Albert Instrument Co. (2) For Permanent Mounting.— Two models, "enclosed" and "water-jacketed," the principal difference being described by these designations. Fig. 26 shows the "enclosed" tube, which is 20" long. The maker recommends that it be used only where ambient temperature does not exceed 150°F. The outer surface finish is polished nickel, to minimize absorption of radiant energy which otherwise would heat the tube although the air temperature might be well below 150°F. The water-jacketed model's internal arrangement is largely similar.

"*Mikrotherm*" (*Paul Braun*) — A German pyrometer sold by some U. S. instrument firms. Radiation is focused by a lens on the junctions of ten small iron-constantan thermocouples (see rough sketch, Fig. 28). The receiving

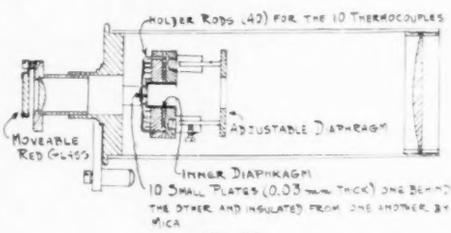

HOLDER RODS (4?) FOR THE 10 THERMOCOUPLES
ADJUSTABLE DIAPHRAGM
MOVEABLE RED GLASS
INNER DIAPHRAGM
10 SMALL PLATES (0.03 mm THICK) ONE BEHIND THE OTHER AND INSULATED FROM ONE ANOTHER BY MICA

Fig. 28

disk is made up of ten superposed individual disks, each welded to a junction. The distance factor is 1 to 20. This instrument is recommended for fixed installation—probably, we suspect, because the time lag is 60 seconds, as well as for the usual reasons. For the range 500-1200°C. the emf. is 21 millivolts at the upper end, according to a series of tests made for this book; for the range 900-1800°C. it is 92.5 millivolts at the upper end.

General Electric Co.—At this writing (1940) this firm supplies only one lens type assembled unit (upper part of Fig. 29) but a choice of two vacuum-bulb radiation thermocouples. These, in fact, are sold as individual items; and the company does not catalog "radiation pyrometers" (though of course the buyer of the receiver unit is not forbidden to buy G-E electrical instruments to go with it). The lag is given in the form of the time-response curve of a 0.5-sec.-period galvanometer: $L_{90} = 1$ sec. and $L_{99} = 2$ seconds. The receiver proper is in the form of a thin (approx. one micron) strip mounted between two "heavy anchor supports" which serve both as the lead wires and as the cold junctions for the single thermocouple. This keeps the

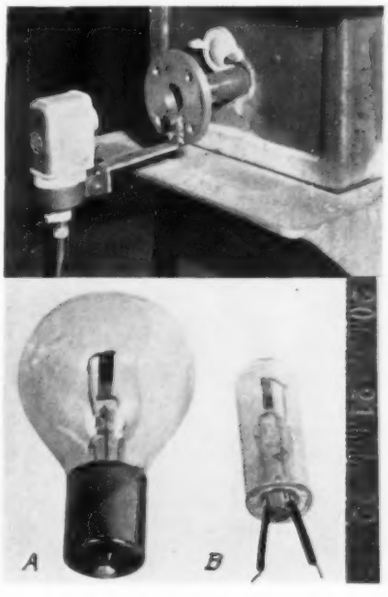


Fig. 29

cold junctions in close proximity to the hot junctions, and, it is claimed, "nearly compensates for any changes in temperature due to internal heating." The emf. is approximately 65 microvolts per °C. the hot junction is at the center of the strip, in the form of a line extending across the strip. The strip is approx. 2mm. wide, is blackened for about 1mm. each side of the junction, thus giving a black receiving area 2mm. square. "These radiation thermocouples were found to be equally responsive to radiant energy of wave-lengths between 0.3 and 3.5μ." Therefore the receiver unit has to be calibrated as installed. More-

over, the convex glass lens should only be used when the source temperature is well above 1000°F.; it should not be included in the assembly when lower source temperatures are to be measured. Without lens, and with the unit close to the source, it is possible to measure temperatures as low as 500°F., depending on the emittance of the source: an oxidized (nearly blackbody) surface 9" from the bulb produced an open circuit emf. (potential difference) of 200 microvolts when its temperature was 700°F.

The *"Pyrradio"* Unit. *Hartmann & Braun* (mfr.); *Brown Instrument Co.'s Portable Unit* (see below for Brown autometric).—Principal feature is the automatic compensation for variations in room temperature, consisting of a crescent-shaped diaphragm controlled by a bimetal-

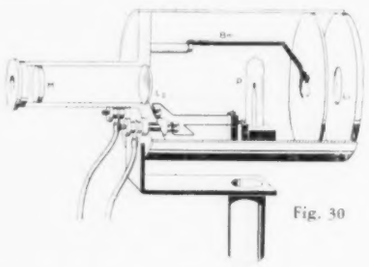


Fig. 30

lic strip between lens L_1 and thermocouple receiving junction disk P. This is said to compensate both for entrance-diaphragm temperature and cold-junction temperature. The distance factors are 1 to 14 for an instrument made up for ranges up to 1200°C., and 1 to 20 for instruments designed for higher temperatures. Above 1400°C. the thermocouple develops more than 30 millivolts, so that vertical-shaft indicators are only required for the low-range unit.

Brown Instrument Co.'s "Radiamatic."—The announcement of this receiver, in the latter part of 1940, contained an exactly quantitative statement of the lag characteristic: "98% of a temperature change in 2 seconds." Applying the thermoelectric-lag (logarithmic-decay) equation to L_{98} gives the "e" coefficient as 0.67, the L_{90} as 1.18 sec. and the L_{99} as 2.36 sec.; also an 86% response in one second. Two "Radiamatic" units are available at this writing: a fused silica lens model for maximum temperatures of less than 2300°F. and a Pyrex glass lens model for higher temperatures. Figs. 31 and 32 are largely self-explanatory, but there may be mentioned that all thermopile junctions are welded. The cold junctions are riveted to a mica ring sandwiched between two other mica rings and the assembly clamped between metallic parts, so that the cold junctions are held at the housing (ambient) temperature. Cold junction compensation is by means of a nickel-coil shunt connected across the thermopile and located in the immediate vicinity of the cold junction. It is said that transient and sustained variations of 250°F. in ambient temperature have a "negligible effect." Each unit is factory-calibrated for blackbody source and the adjustment sealed. As with gas and electricity meters, an authorized person may change the calibration and re-seal. The adjustment range is approximately —10% to +20% in terms of thermopile emf. Distance factor, 1 to 20. Minimum target diameter, 1⅜".

P. J. Kipp & Zonen—This Dutch firm (known for its astronomical thermopiles) manufactures two models of a radiation receiver which has no fewer than 18 thermocouples in series, the elements being constantan to manganin. The lags are 2 seconds for the thermopile to attain temperature and 3.7 seconds for the full deflection of the electrical instrument furnished by this manufacturer.

"Iscometer" (*W. H. Joens & Co.*, Germany)—This is a receiver connected by means of a long metal tube to a closed-end refractory tube. The sensitive element is a thermopile which develops 75 millivolts at top of scale range.

7. Notes on Calibration and Errors

Calibration

The receiver is pointed at a nearly perfect blackbody, which is either found in some furnace where the conditions are suitable (see Section 3) or can be made up by winding an electric heating coil around a porcelain tube closed at one end, as described in various scientific publications. The essential requirement is that the temperature of the blackbody be accurately measured by means of a good standard pyrometer. Another requirement is purity of atmosphere between source and pyrometer, if true "calibration" rather than "checking" is desired (see Section 4). Therefore, if you use a closed-end tube in an industrial furnace, and an optical pyrometer to calibrate your radiation pyrometer, make sure that the refractory is not porous to infrared-absorbent gases such as CO and CO_2.

As with most other industrial instruments, the important thing in the large majority of applications is not so much to measure the *true* temperature as to be able to

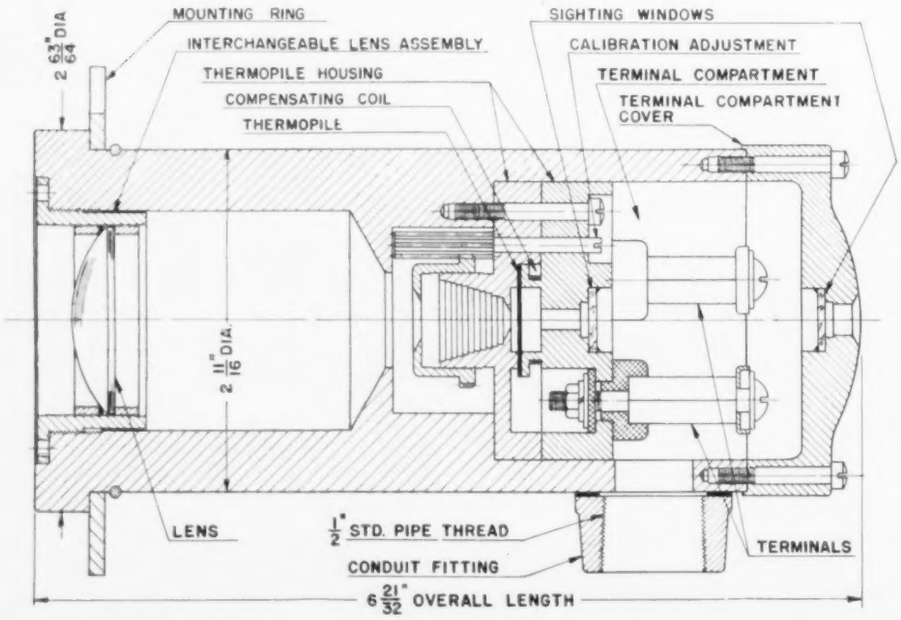


Fig. 31

Sectional view and close-up of thermopile of "Radiamatic." *(Brown Instrument Co.)*

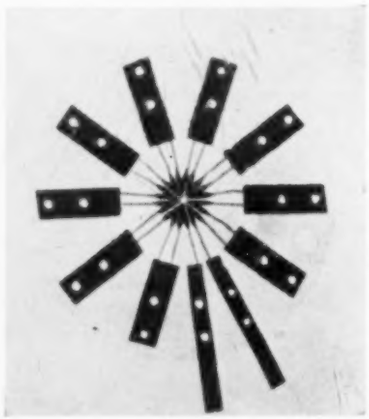


Fig. 32

produce temperature conditions day after day. Therefore, check up your radiation pyrometers fairly frequently not to make sure that they measure the exact temperature, but simply to make sure that they have not "gone bad." The radiation receivers, the electrical instruments used in connection with them, and the self-contained industrial radiation pyrometers, while not entirely fool-proof, should "stay put" in their indications for months—and sometimes for years of service. *Above all, keep the collecting lenses and mirrors clean!*

Miscellaneous Errors of Radiation Receivers

Some of the topics below have already been discussed, but they bear repetition.

Factory calibration assumes that the receiver proper will not be exposed to stray radiations beside the heat of the source being measured. The sensitive element "sees" the object or its reflections over a wide-angle of vision, but the remainder of its *sphere* of vision must not be forgotten.

In the Féry type, for instance, if the window or diaphragm closest to the disk is overheated, a ring of invisible heat radiation, surrounding the principal beam, will also fall on the disk. This effect is largely compensated by the optical properties of the mirror—when variations in diaphragm temperature are due to varying distances from the object. When the distance is fixed and the effect is caused by variations in furnace opening, the errors cannot be compensated. Follow the manufacturers' specifications for sighting-hole dimensions.

In open-tube receivers, where the rays are reflected to the disk from almost all around it, the disk "sees" the source *directly* over a narrow cone. It sees its *reflection* over a wide cone of "vision" (almost a sphere in the Twing receiver). But it also sees other parts of the instrument, such as diaphragms. Applying extra heat to these surfaces will cause the indicator or recorder to read too high; cooling them unduly will cause low readings. Ventilation features do much to obviate such undesired variations.

The instrument reading in thermoelectric types depends on the *difference* in the temperatures of the hot and cold ends of the couples. In some designs the cold junctions are so shielded from the radiation and other heat sources that fluctuations in surrounding air temperature should not cause serious errors: each end is equally affected. This does not constitute complete compensation for the temperature waves to which *hand* pyrometers are subject.

With thermocouples sealed up in bulbs there is a residual heat effect, noticeable as hysteresis. When taking readings in succession it is well to give the bulb time to cool off. It takes longer for the sealed-up disk to come to room temperature than for the cold end. "Rest" a portable instrument between readings and make these short. When the receiver is permanently installed, prevent rapid temperature fluctuations around it, unless it is completely water-jacketed.

With a fairly constant-temperature source of radiation, you can determine for yourself the effects of varying the distance of the receiver. Start farther away than the manufacturer recommends; take readings at known distances; approach as close as conditions permit, take readings again as you recede. Plot the curves. The results will point the way to the best practice.

Another interesting series of tests applies only to the collecting-lens receivers: Note how the maximum permissible working distance varies with the *temperature* of the furnace. The reason is that the higher the temperature, the wider the spectrum, and the "thicker" the image, since the lens is not "achromatic" for "total" radiation. Camera enthusiasts will know how to minimize this tricky source of error.

A closed-end refractory tube of the proper material for giving blackbody or at least graybody conditions is recommended for permanent installations. Chief requirement is constancy of atmosphere in tube: if absorption of radiant energy by gases and fumes cannot be avoided, keep it down and keep it constant.

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Classification and Characteristics of Prime Relays

Second half of third instalment of new and revised edition of "Temperature Measurement and Control." This is one of the sections of the chapter on Temperature Control Principles.

By M. F. BEHAR

In Chapter I it was mentioned that one of the ways of classifying all industrial temperature instruments is also (1) direct-acting or direct-writing or direct-deflection or self-operated and (2) all those employing an external source of power. The latter are called "relay" or "servo-motor" instruments. Both designations are exact, because a device or system of this kind makes use of a relatively powerful servant and commands this servant by means of some arrangement which we may call a pilot or relay.

Let us first of all consider the most important — the *prime* or *initial* relay—the one immediately associated with the measuring element—because in some complicated systems there are several servants or, to be more precise, several "stages."

Note—The ILLUSTRATIONS have been selected to bring out unusual rather than common and well-known cases and characteristics. They have been selected for this ARTICLE and do not represent the final choice for the BOOK which is being given its final revision.

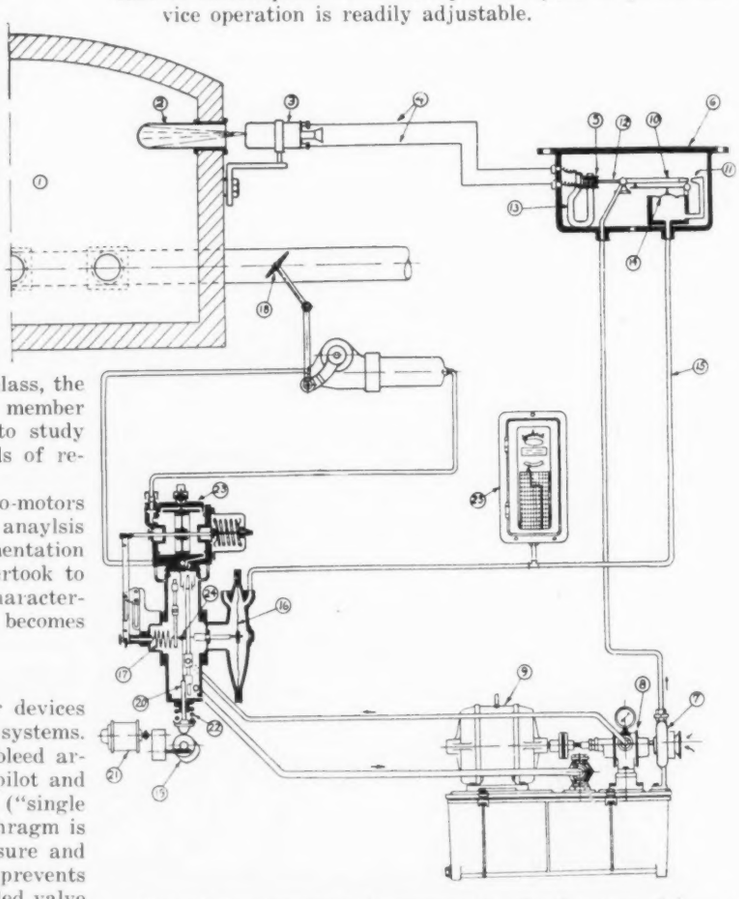


Fig. 1. In this furnace temperature control system the PRIME relay (6) actuated by radiation-pyrometer primary measuring system 2-3-4-5-13, is PNEUMATIC and its function is to actuate a hydraulic relay, whose function in turn is to operate the fuel valve. Both the pneumatic prime relay and the hydraulic "power" relay are of the "jet-pipe" type, but with the difference that the former requires only one orifice (11) whereas the latter requires the usual two orifices. Another unusual feature is the intimate association of the permanent-magnet-moving-coil electrical element 13-5 and the pneumatic relay: coil 5, which floats in field of magnet 13, is carried by arm 12 which is continuous with jet-pipe 10, so that one pivot serves both the electrical movement and the prime relay which it commands. *(Askania)*

In any temperature control system of the relay class, the *primary measuring element* is the most important member of the team; and the "*prime relay*" is the one to study with greatest care. To study these numerous kinds of relays we must classify them.

Although the literature on relays and on servo-motors would fill a five-foot shelf, this classification and anaylsis had never been done from the viewpoint of Instrumentation until about three years ago when the writer undertook to make a *tentative* classification and summary of characteristics—both subject to revision when terminology becomes somewhat standardized.*

1. Pneumatic

This class is mostly made up of compressed-air devices but it includes vacuum systems and gas-operated systems. Characteristic feature of the usual dead-end and bleed arrangement is a single controlled-air line between pilot and power device, so that the action is unidirectional ("single action"). In the usual power device a flexible diaphragm is urged in one direction by the compressed-air pressure and in the other by a spring. The characteristic "give" prevents locking-in-place of power device and, if the controlled valve is imperfectly balanced, load error ("droop" is inevitable.

However, there have appeared secondary pneumatic relay systems known as "regulators," "valve positioners," etc., which provide micrometric lock-in when properly adjusted. Some are double-action systems comparable to the hydraulic class.

Most primary pilots, directly actuated by the measuring elements, impose practically no *variable* drag on the measuring elements; and some of the newer fully-balanced and floating designs are entirely free from metal-to-metal friction.

Pneumatic-relay instrumentation is relatively inexpensive (except where large high-pressure valves must be commanded: the lower cost of electric motor-driven valves may then offset the differences in all the other elements of the systems). Compressed-air storage tanks assure safety in case of interruption of electric power. Speed of power device operation is readily adjustable.

Recent developments in pneumatic circuits comprising a plurality of relays (similar to "cascading" and "feed-back" with electron tubes) have added *stability* and have thus made the pneumatic system capable at last of meeting difficult variable-load requirements. (However, it may be worth mentioning that the modern pneumatic relays were invented and developed *by* instrument men *for* instrument men.)

1A. Steam

This class shares some characteristics of the pneumatic class and of the hydraulic class. Most conventional steam pilot valves, operating double-action cylinders, require so much energy for their actuation that only the relatively

*The trouble has been, it seems, that the terminologies used by writers on relays and on servo systems have been all mixed up. For example we find the adjective "electronic" applied to many devices in which electron tubes play a subordinate part or even to devices in which there are no electron tubes at all.

Great as is the debt which we owe to radio engineers, we can't permit this confusion to go on, and therefore my tentative classification purposely gives a narrow definition to "electronic" relays.

Another difficulty relates to the standardized terminology of electrical engineering—which I would not dream of changing. In electrical engineering, most "relays" embody measuring (or "responsive") elements and operate automatically, so that from the viewpoint of Instrumentation they are not relays but "automatic controllers."[5] Throughout the following discussion, the relay is the means whereby the measuring element is enabled to command a servo mechanism without doing any other work.

powerful primary measuring elements can actuate them without suffering impaired sensitivity. However, there are many valves, modified needle valves and bleed arrangements, together with single-action diaphragms, etc., whereby a small simple mercury or vapor-pressure temperature measuring element, for example, is enabled to actuate the "relay" part in a satisfactory manner. No need to dwell on the fact that disposal of exhaust and condensate create complications not present in pneumatic relay systems.

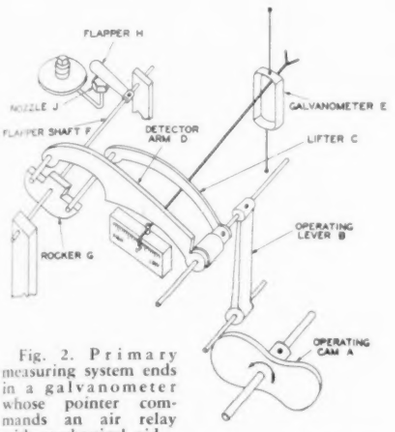


Fig. 2. Primary measuring system ends in a galvanometer whose pointer commands an air relay with mechanical aid—the power being supplied, however, by an electric motor not shown. Note that although the pointer is clamped cyclically, the mode of control is "stepless" or "proportional." *(Foxboro)*

Two examples of MECHANICAL Prime Relays, actuating respectively: (Fig. 2) a pneumatic relay, (Fig. 3) electrical relays.

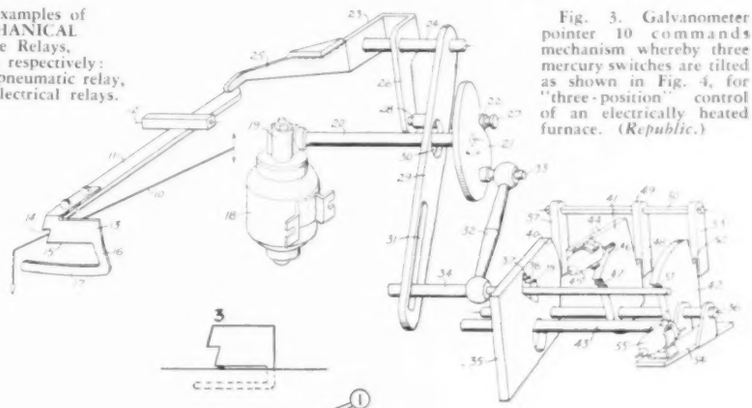
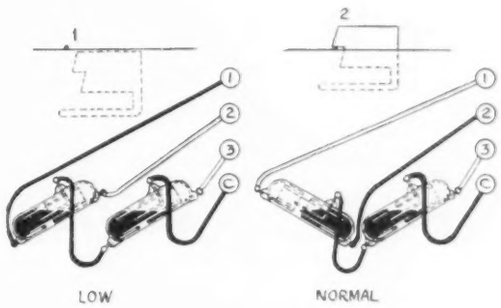


Fig. 3. Galvanometer pointer 10 commands mechanism whereby three mercury switches are tilted as shown in Fig. 4, for "three-position" control of an electrically heated furnace. *(Republic.)*

Fig. 4. Showing how the mechanical prime relay of Fig. 3 is commanded by the galvanometer pointer and in turn commands the three mercury switches. *(Republic.)*



2. Hydraulic

Although the Greek root means "water," this class comprises all systems where an "incompressible" fluid is the operating medium. In control systems, oil is most frequently used. Ample power, positive operation and possibility of locking-in-place of power cylinders are the most obvious characteristics. In general the action is relatively slow, but accurate adjustment of speed is an advantage. On the other hand, jerky action is all too frequent in some cheap systems.

Most longitudinal-motion pilot valves consume too much energy to be suitable for actuation by electrical movements and by most other measuring elements. This undesirable erratic drag effect has been minimized in the newer pilots and almost eliminated in the Hagan longitudinal-motion type pilot relay and in the Askania pivoted "jet pipe" relay. Prodigious ingenuity is evident in recently invented hydraulic circuits (mostly inspired by those of turbo-generator governors) which permit achieving results close to perfection.

3. Mechanical

Few mechanical relay and amplification systems have been utilized by industrial instrument designers. It is mostly in the recording, integrating and totalizing instruments that one finds them. The enormous disproportion between the total number of classes and types of escapements, clutches, triggers, torque amplifiers, etc., and the total number in use precludes further discussion here, except to invite attention to the fact that the proper performance of many recording and controlling instruments employing mercury switches, electric contacts, electric-motor chart drives, etc., depends upon the correct functioning of mechanical relays actuated by feeble measuring elements and in turn operating the electrical devices.

4. Electrical

The great majority of electromagnetic relay systems in industrial instrumentation are "on-and-off" devices whereby circuits are instantaneously opened or closed. The simplest are those wherein contacts are directly attached to the pointers. These are "electric" rather than "electromagnetic" and they naturally divide themselves into single-contact, high-low, and so-called "three-position." Next come the true electromagnetic relay arrangements, whereby relatively delicate contacts at the pointer actuate power relays with relatively high ratings. ("Power relays" here denotes a great variety of switchgear all described in readily-accessible electrical-engineering handbooks.)

The two principal classes of power devices commanded by the measuring element through electric and magnetic relays are (1) solenoids and (2) motors. In general, solenoids provide practically instantaneous action and motors permit a choice of speeds.

Although most electromagnetic relays are "on-and-off," there are several types which provide "throttling" modes of control—some step-by-step, others *continuously-variable*. The simplest arrangement, to have the instrument pointer "wipe" a rheostat, imposes a drag on the measuring system and as a rule can only command another pointer type

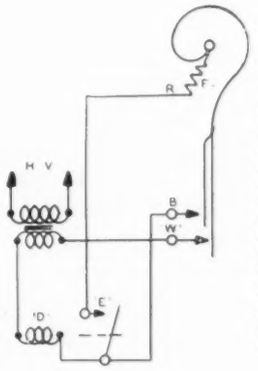


Fig. 5. Contact-making is the simplest electrical prime relay idea, but not the least capable of interesting possibilities. Here, for example, an "ordinary" room thermostat employs contacts to provide an "anticipatory" mode of control. Heater *F*, in "holding" circuit with contact *E*, causes thermostat head to heat up faster than it would if it "waited" for room to heat up to control point. Thus breaking contact *W* is accelerated. But contact *B* must be broken by normal temperature rise at thermostat. To energize second electric relay *D* and start burner, *B* and *W* close in conventional manner. When *D* closes, holding contact *E* is made. Time of burner operation thus depends on *rate* of temperature rise. *(Minneapolis-Honeywell)*

instrument. A modification is to have the pointer "wipe" a voltage-dividing resistor (commonly and erroneously called a "potentiometer") which in turn positions a solenoid-and-contactor balancing arrangement commanding a rela-

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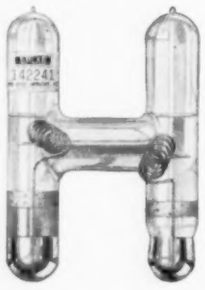

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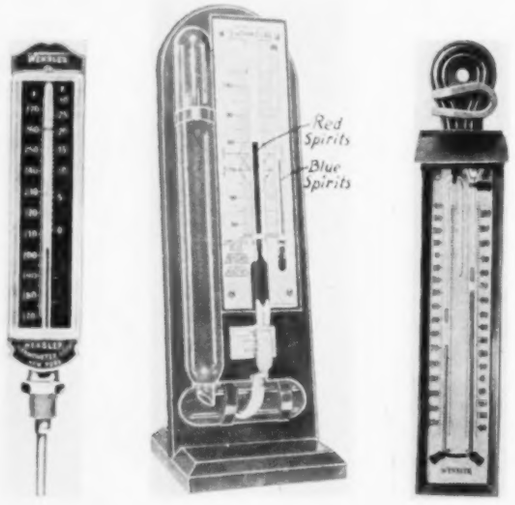

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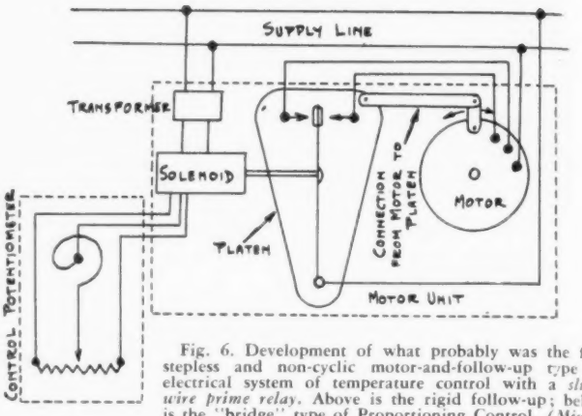
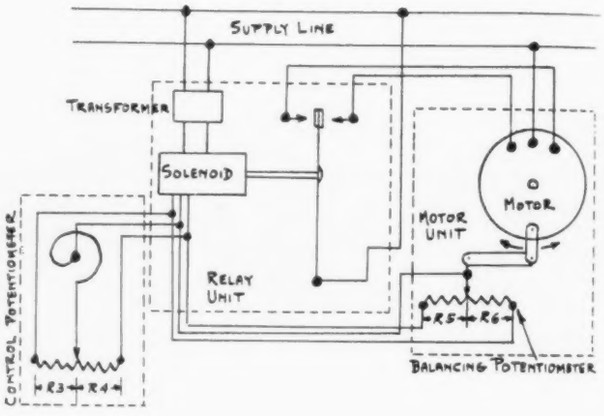


Fig. 6. Development of what probably was the first stepless and non-cyclic motor-and-follow-up type of electrical system of temperature control with a *slide-wire prime relay*. Above is the rigid follow-up; below is the "bridge" type of Proportioning Control. *(Minneapolis-Honeywell.)*



tively large motor. Another modification is the Brown-Boveri rocking-contact type of resistor which is so frictionless that a damping device to prevent overshooting is a standard part of this "pilot." Another "step-less" arrangement is found in the G-E "Silverstat." Various other continuously-variable electrical relay systems have been developed.

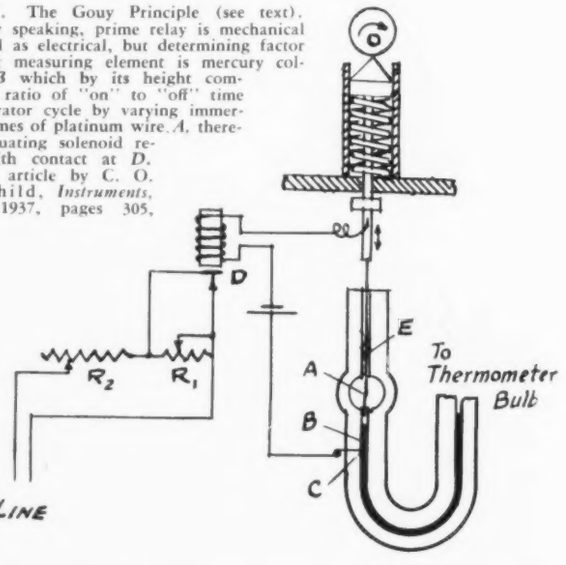


Fig. 7. The Gouy Principle (see text). Strictly speaking, prime relay is mechanical as well as electrical, but determining factor is that measuring element is mercury column *B* which by its height commands ratio of "on" to "off" time in vibrator cycle by varying immersion times of platinum wire *A*, thereby actuating solenoid relay with contact at *D*. (From article by C. O. Fairchild, *Instruments*, Dec. 1937, pages 305, 317.)

The effect of a continuous variation or "throttling" is obtained by vibrators and other circuit-interrupting devices (some of which are combination mechanical and electrical relays) whereby the closed-circuit time in each cycle of operation is a function of the position of the pointer. The resulting mode of control is applicable only to processes with adequate energy storage or "flywheel effect." There-

...e this equivalent of throttling is chiefly used for the con... of electric heat. Modern high-rating inverse-time re... for such heavy duty as furnace temperature control h... periods of one to five minutes. Other temperature con...llers have periods of down to a few milliseconds. The o...ginal inverse-time cyclical interrupting device, invented ... Gouy in 1897, held the temperature of a bath within 0.005°C. but was of relatively low wattage. Its modern analogues are used in the Tagliabue "Celectray" system and in some "vibrating" types of themoregulators.

5. High-frequency Electrical

This designation has been adopted to convey unmistakably the idea that this class of relay systems utilizes the properties of a-c. networks. (Since most a-c. phenomena manifest themselves at low [commercial] frequencies, the designation "a-c. relays" would be correct, but in electrical engineering terminology it already denotes a class of devices different from the systems here considered.)

The outstanding characteristic of high-frequency electrical relays is the possibility of eliminating drag by doing away with contacts and pilot valves. In some systems the pointer or equivalent element serves as one plate of a variable capacitor, in others it serves as the control element in an inductive coupling, the mechanical reaction in either case being negligible.

Fig. 8. The first industrial temperature control system to use a high-frequency type prime relay (capacity variation) was the "Capacitrol" brought out in 1935. Note the mercury switch secondary relay. There is nothing "electronic" about such prime and secondary relays. *(Wheelco)*

Aside from these pointer-displacement systems there are others in which the relay action is effected *without any mechanical motion at all.* These latter, of course, can only be used in conjunction with "static" (no-moving-parts) measuring systems in which the measured temperature is translated into an exactly proportional electrical magnitude. This representative electrical magnitude need not itself be an a-c. effect: the feeble d-c. output of a thermocouple, for example, can be used as the controlling input.

Relay systems of this class are erroneously called "electronic" in nearly all booklets describing the recorders, controllers and telemetering system in which they are used. This is incorrect even when electron tubes are used incidentally.

Among the most sensitive systems of this class are resonant networks adapted from radio and employing electron tubes as "servants" of the prime relay. The earliest ones (1931), actuated by capacitor primary elements, employed tuning phenomena and radio tubes. So did the first ones for industrial temperature control (Wheelco Instrument Co., 1933). But while they may all be said to use a "radio principle," they should not be classified as electronic relay tubes.

6. Electronic

In this newest class of instrumentation relay systems the *relay proper* is an electron tube, directly actuated by or fed from the measuring element or system. Although relatively few of the hundreds of commercial types of electron tubes are suitable as prime relays, other types are employed in the numerous circuits which have been developed to take full advantage of the general characteristics of electronic relays.

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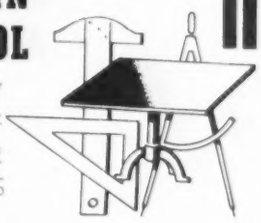

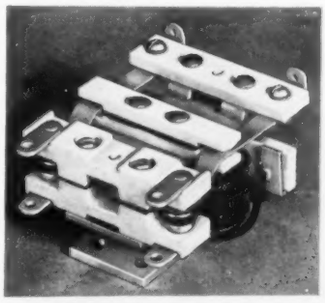

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First among these general characteristics is suitability for actuation by static (no-moving-parts) measuring elements. Conversely, no ordinary pointer-and-scale type of measuring element can be equipped with an electronic relay; and no ordinary type of electron tube can serve as a relay in conjunction with a mechanical-displacement type of measuring element.*

Second outstanding general characteristic is enormous amplification: up to 1500× in each stage. Third general characteristic is instantaneity. Other general characteristics (to which there are exceptions) are: limited life, gradual or sudden alteration of tube constants without outward sign, fragility, low cost of "spares," ease of replacement, and relative instability where the "signal" from the measuring element is of the order of millivolts d.c.

Electron tubes differ from all other relays in that while the "constants" of a tube are mostly inherent and are intended to be unaffected by external factors, its operating

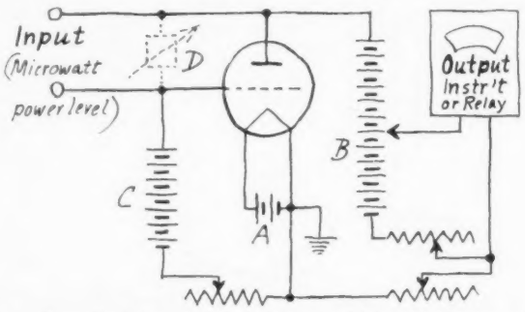

Fig. 9. Generalized diagram of method of utilizing an electron tube as the prime relay commanded by (fed from) a feeble measuring element. (Actual hook-ups may be simpler.) An electrometer type tube amplifies the signal sufficiently to operate a power relay. Nature of device *D* depends on source and nature of input signal: if source is of practically infinite internal resistance and signal a d-c. potential, *D* should be a resistor of the order of megohms; if signal is a. c. or "chopped," *D* should be a capacitor.

characteristics depend on external factors such as ambient temperature, character of signal, whether the load is purely resistive, inductive, capacitive or combination, etc.

Inherent electron tube characteristics depend on interrelated features of design and construction. With regard to the character of the space there is a twofold division: (1) Vacuum tubes, being evacuated down to a pressure of a millimicron or less, have a nearly infinite resistance when no potential is applied and thus are "voltage-operated" devices, provide the best means of accurately controlling the flow of electrons and therefore are the most suitable for amplification duties but (except for rectifiers and oscillators outside our scope) have low ratings —milliwatts to a few watts. (2) Gas-filled or vapor-filled tubes, evacuated then filled with a pure gas or vapor at pressures between 5 and 500 microns, have a relatively low and constant voltage drop between anode and cathode, can carry relatively enormous currents and are widely used as rectifiers, variable-resistors, trigger-effect power switches, etc., but the linearity of their characteristics is seriously affected by temperature and other factors.

With regard to types of cathodes there are (1) thermionic, (2) photoelectric, (3) cold and (4) pool, only the first two being commonly used in measurement work and only the thermionic tubes being suitable for service as prime relays directly actuated by any measuring elements having electrical outputs.

With regard to structure, the diodes are unsuitable because they have no control electrodes, but while all others are suitable the triodes and screen-grid tubes are the ones chiefly used up to now for instrumentation relay service.

With regard to control of the electron stream there are (1) electrostatic means such as grids, plates, etc., (2) electromagnetic means, generally coils outside the glass envelope, (3) combination tubes. All of these are suitable in

*Phototubes are not electronic relays: even in a photoelectric-optical pyrometric system where "brightness temperature" is measured and controlled, the phototube cannot be the relay because it is the measuring element. The same is true of a mercury-vapor type grid-controlled rectifier when used as the temperature-responsive element in a thermostat.

inciple, so that practical considerations of dimensions, ight, cost and availability are the ones that have caused e familiar electrostatic-control tubes to be adopted almost clusively. The same applies to cooling means, water-oled tubes introducing an undesirabe complication in in-rument work.

As to the nature of the envelope there are (1) glass d (2) metal tubes, the characteristics being fragility and availability—metal tubes still being relatively scarce at the time of writing.

Summing up, we may say that the single "type" most suitable for relay service as understood here, may be described as follows: high vacuum, thermionic-emission or heated cathode, amplifier tube with one or more electrostatic control electrodes.

So numerous are the built-in means of control (including "inversion" schemes with grid anodes, etc., specially designed for measurement work) and the external methods of control ("hook-up") that further discussion cannot be attempted here.

7. Photoelectric

This class of relays comprises both phototubes and photocells. Outside the field of Instrumentation the former are considered "electron tubes" and in nearly all texts they are lumped together with the electronic relays discussed in the foregoing paragraphs, while photocells are excluded. For our purpose the only criterion is that electronic relays respond to purely electrical effects and have purely electrical outputs; whereas photoelectric relays are all those which respond to light and have electrical outputs.

There are three classes of such devices: (1) "selenium" or photoresistive tubes and cells—originally the only ones but seldom used for instrument work today; (2) photoemissive, comprising various forms of vacuum and gas-filled glass tubes with various forms of cathodes coated

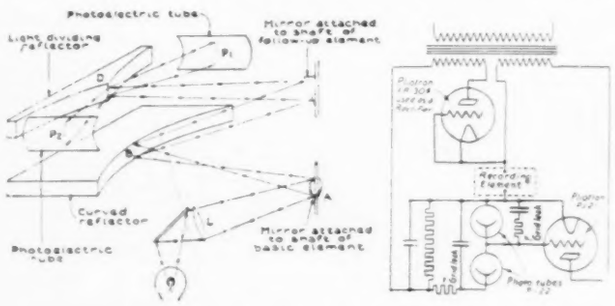

Fig. 10. The first industrial photoelectric prime relay proportional follow-up was brought out in 1932 and embodied in a relay recorder. Mechanical and electrical diagrams show how two phototubes are used. *(General Electric.)*

with various alkali-metal materials; (3) photovoltaic or blocking-layer, theoreticllay comprising all types but in practice excluding the Becquerel liquid electrolytic cells and made up only of the dry disk form cells—chiefly cuprous oxide on copper but lately including selenium-on-iron and other new developments.

All are widely used as measuring elements but this is not the function considered here. The outstanding characteristics of all phototubes and photocells, *used as relays*, are (1) total absence of drag on the measuring element; and (2) practically instantaneous response — the lag of the "selenium" and blocking-layer classes being negligible in relay service.

Other characteristics differ widey with the classes and types. There is no such thing as a phototube or photocell with perfectly and permanently linear characteristic of electrical output to intensity of illumination: all suffer to some extent from fatigue, temperature coefficient, etc., but these effects are immaterial in the simple trigger relay applications. Therefore, in applications requiring proportionality, phototubes or photocells are preferably used in *pairs* and the deflection of the measuring element determines the *ratio* of the light falling on each.

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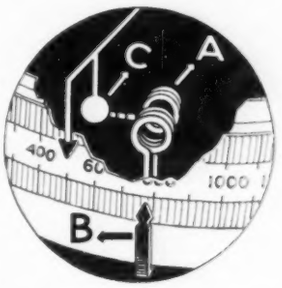

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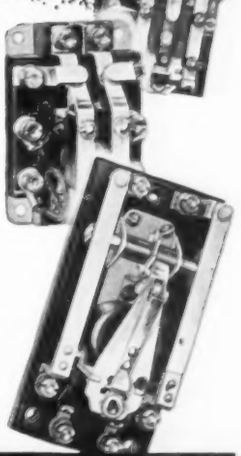

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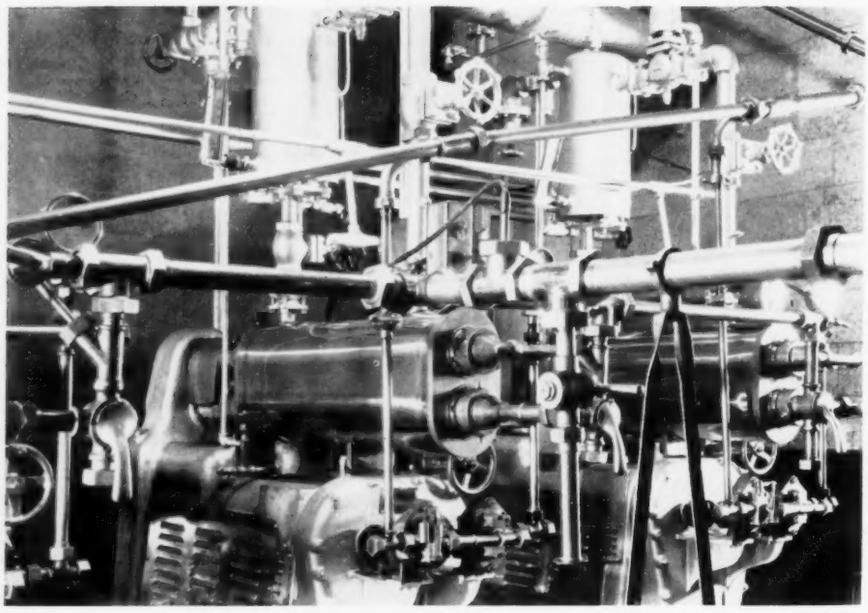

Fig. 1

Temperature Instrumentation for the Continuous Ice Cream Freezing Process

Awarded an Honorable Mention in the Second Annual Instrumentation Contest

By the Technical Staff of
Abbotts Dairies, Ltd.
Philadelphia, Pa.

IN the last four years the manufacture of ice cream has been revolutionized by the continuous freezer. The rate of freezing is so rapid in these high-speed machines, and the finished product is so sensitive to small changes in operative conditions, that accurate measurement of the temperature of the product leaving the freezer is essential. If the temperature is too low the finished ice cream will have a "cold cream" texture; if too high it will be coarse and icy. A novel application of electrical resistance thermometers, supplanting mercury-in-glass thermometers, will be described.

First, a brief outline of the continuous freezer process: The cream in liquid form, mixed with the required flavoring materials, is put into a large tank on the floor above the freezer. A pipe line with suitable valves leads from the tank to the freezer and through this line the liquid cream flows by gravity. Each freezing machine has its self-contained electrically-driven ammonia refrigeration system, together with an air injection device and gear pressure pumps. The first pump runs fairly slowly and delivers a measured quantity of cream per minute to the other pump, which runs much faster. This creates a suction. A measured quantity of air is allowed to enter the line between the two pumps. This air is essential: without it the ice cream could not be eaten for nothing but a solid hard block of frozen cream would result.

Fig. 1 shows two of a gang of three freezer units connected to a common outlet pipe. The cream enters the front of the freezer through the pressure pump which is required to force it through the piping after its temperature has been reduced. This usually takes a pressure as high as 70 lbs./in.^{2}. The cream which emerges is about the consistency of a soft paste which will just hold its form without running and its temperature is around 22°F. It is frozen in passage through the two refrigerated freezing cylinders, the mutator inside having sharp blades and a speed of 700 r.p.m. The temperature is controlled manually by adjusting the refrigerating device. The quality, smoothness and rate of production of ice cream all depend on accurate control of the temperature of the cream as it comes from the freezer. Also differently flavored creams, for best results, must be controlled at slightly different temperatures within a range of only 0.2°F.

Mercury-in-glass thermometers, graduated in tenths of a degree Fahrenheit, were employed. One mercury thermometer required considerable attention from one of the attendants handling the container filling device. This was stirred periodically in the cream in some of the filled containers moving on a traveling chain. Frequent errors in readings caused considerable variations in temperature during a run. Often, when the thermometer was not carefully handled, it was broken in the ice cream. (Result, an expensive thermometer destroyed and a large container of cream wasted.) Because periodic tests were made, accurate control was impossible, for after determining the temperature of the cream coming from the common line of a gang of freezers it was necessary for the attendant to walk from one to another of the pipe line thermometers to determine which freezer unit needed adjustment. Stem errors in the pipe line thermometers were not easy to determine or compensate for. Trouble with separated mercury columns was frequent.

All these factors led to a search for a temperature measuring equipment which would be automatically accurate and reliable, read easily by the attendant, and not subject to frequent breakages. An equipment consisting of a set of nickel resistance thermometers, an indicating recorder and a selector switch was supplied by an instrument manu-

Fig. 2

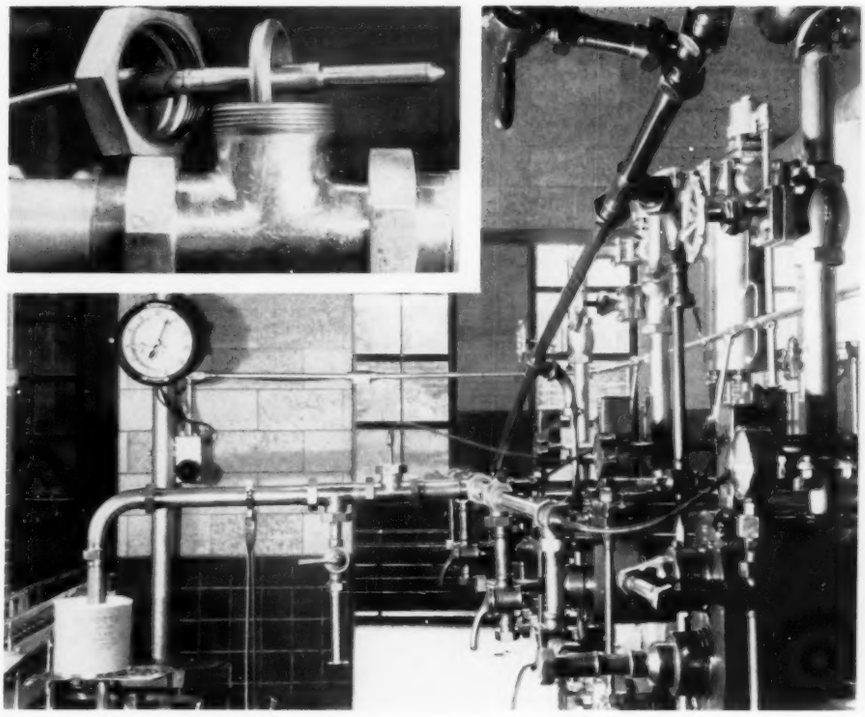

Fig. 3

facturer to cover a range of 10°F. to 30°F. with readability to a tenth of a degree. Fig. 2 shows a disassembled view of a pipe line thermometer. The thermometer coil, wound on a metal spool having on it an end brazed into the tip of the stainless steel protecting tube, put the temperature measuring point right into the middle of the ice cream stream, eliminating conduction errors. The top end of the thermometer is vulcanized to a flexible rubber-covered cable. All parts are smooth and accessible for cleaning. The thermometers are so rugged that no breakages have occurred in over 18 months of service.

The dial switch is set to make the indicating recorder read continuously the temperature of the ice cream in the common outlet lines. It is evident from Fig. 3 that the attendant has no difficulty in reading the indicating device accurately even from a considerable distance. Another advantage is the possibility of determining individual freezer outlet temperatures by turning the dial switch at the instrument. Figs. 1 and 3 show the locations of the various thermometers in tee fittings.

The records of runs for different flavors have proven to be valuable guides for future production. When a particularly good run of ice cream is obtained, the record made during the run is kept as a standard of operation.

Production is speeded up with the same number of attendants because none of their time is used for handling a testing thermometer. Frequent checks of the automatic equipment were made when it was first installed but the equipment has proven so reliable that checks are now made only once a month. The indicating recorder motor and measuring circuit are supplied from the regular a-c. lighting circuit—batteries are not needed.

An interesting fact not previously suspected was learned from the use of the resistance thermometer equipment. It was found that the ice cream in the common outlet line from the freezer was always at a lower temperature than the ice cream just at the outlets of the separate freezer units. There is sometimes a difference of more than half a degree and this has been checked many times. No definite explanation for this difference has as yet been offered. Perhaps some of the readers of this article may be able to give an easily understood explanation.

INSTRUMENTS' BOOK SHELF

The Decline of Mechanism in Modern Physics. By A. D'ABRO. D. Van Nostrand Co., Inc., New York, 1939. Cloth, $6\frac{1}{4} \times 9\frac{1}{4}$ inches, x + 982 pages, Price $10.

Nearly a thousand pages; nearly half-a-million words. Here indeed is one of those "monumental" works on modern science destined to endure for decades as recommended texts in spite of the increasing rate at which new theories are being postulated. Mere length, of course, would not justify beginning a review with so enthusiastic a prediction, so we hasten to add (1) that the quality of Dr. D'Abro's words matches their quantity and (2) that we make this assertion after having read—with intense enjoyment—thirty of the book's forty-one chapters. The other eleven chapters, we believe, are a wee bit too purely mathematical for readers who graduated from engineering school in the days when an ambitious student could not have found tensor analysis and the new matrix short-cuts on the school curriculum even if a prophetic dean had advised him to take these courses.

But perhaps this minor fault-finding is unjustified. Dr. D'Abro states, in his Preface, that "some of the subject matter might have been omitted" and explains at length his reasons for including such chapters. We quote a few lines: ". . . We have included a brief discussion of the Problem of Three Bodies because the tremendous mathematical difficulties which beset this seemingly simply mechanical problem show how the progress of theoretical physics may be delayed by purely mathematical obstacles. For a somewhat different reason we have given a summary of the controversies on the nature of mathematics. In our opinion these controversies originate from the same psychological differences which appear to be responsible for the current controversy concerning the principle of causality in physics . . ." These chapters which "might have been omitted" are XIV, XVI, XVII and XX. Also, Chapters XXVI and XXVII "might have been shortened."

Dr. D'Abro ends his Preface as follows: "The non-mathematical reader should experience no serious difficulty in following the presentation, especially so since the more technical chapters (Chapters XXXI to XL) are not essential to a general understanding of the new ideas, and may be omitted in consequence." These are nine of the last ten chapters. Add them to the four which "might have been omitted" and to the two which "might have been shortened" and the total is fifteen. Fifteen out of forty-one! Surely no previous author of a consecutive text has ever told his readers to skip so large a percentage of his chapters! Most authors beg that every line be read. As a matter of fact, we did not find all of the nine "technical" chapters too technical; but we merely glanced through certain of the recommended chapters without feeling any desire to grasp their sub-

jects thoroughly. The eleven chapters we thus "neglected" because of insufficient interest or insufficient mathematical knowledge are more-or-less *scattered* throughout the entire volume. We believe that the "average engineer" who is genuinely interested in modern physics will likewise find Dr. D'Abro too modest. The younger engineering graduates (particularly those from universities with "progressive" physics departments) should not find Chapters XXXI-XL too technical.

(Needless to say, we are reviewing this book *as* an engineer *for* engineers. Professional physicists have already hastened to bestow their praise on this masterpiece.)

Now for a reportorial review: The book comprises three Parts, each a veritable "book":

I—General Considerations. Fundamental, absolutely non-mathematical, really fascinating from beginning to end.

II—Physical Theories of the Classical Period. Necessarily mathematical but not technically so. In other words, these chapters "on" mathematics are written with the "physical significance" mode of presentation as their purpose. For example, as early as the fifth page, the author brings in Schrödinger's equation of the hydrogen atom but without writing it: he tells the story and points out its "moral." The chapters which the Preface states "might have been omitted" are worth reading for their own sake, as if they were articles in a semi-popular scientific journal Moreover, the most "detached" discussions (such as the delightful essay entitled "Intuitionists and Formalists") turn out to have a distinct bearing on the later chapters, as one discovers when he has been reading the book over a period of two or three months.

Part III—The Quantum Theory. This is virtually a self-contained text on almost the entire field of modern physics, emphasizing discussions of various quantum theories and driving home the differences between the classical physical universe and the universe of subatomic phenomena, but by no means neglecting the differences between pre-Einstein and relativistic views of cosmic-scale phenomena. Here is the opening paragraph of this 534-page Part:

"The Theory of Relativity and the Quantum Theory are the two latest products of natural philosophy in physics. They are not opposing doctrines between which we must choose; they are complementary, covering different fields."

In spite of its length, this book has evidently been written from beginning to end with painstaking care. One reason for its length is obviously the author's determination to drive home every important idea, particularly the new concepts, by the use of every legitimate pedagogical and rhetorical device Noteworthy example, the 43-page discussion of Heisenberg's Uncertainty Principle—a masterly exposition, putting to shame those jumping-at-conclusions physicists who, abandoning logic for theology, seized upon the inexact and ambiguous word "indeterminacy" and went off into fantastic dissertations on "free-will" as if Heisenberg's principle had contributed to the assumption that the course of nature is not determined.

No science writer since the days of Arago, Flammarion, Kelvin and the other great expositors of the last century has ever expressed himself with greater clarity than does Dr. D'Abro. In exactitude, his amazing facility for choosing *le mot juste* makes this book tower high above those of most other modern popularizers writing in English. (C'est seulement en francais qu'un physicien peut exprimer ses idées parfaitment et précisément.) In elegance and polish—as a consequence of its lucidity and exactitude, rather than as a result of specific stylistic efforts—this treatment of modern physics will rank almost as high as those of such masters as Darrow, Jeans and Eddington.

And a final word of appreciation to the publishers for making this "thousand-pager" easy to handle as well as durably bound—thereby protecting the physical form of a good ten-dollar investment.

—M. F. BEHAR

The Tools of the Chemist, Their Ancestry and American Evolution. By ERNEST CHILD; foreword by C. A. BROWN. Reinhold Publishing Co., New York, 1940. Cloth, 5¾ × 8¾ inches, 220 pages. Price $3.50.

The author, who for years was with Eimer and Amend, one of the largest and oldest apparatus supply houses of this country, gives in this book an able review of the development of the scientific laboratory apparatus industry in the United States from its European origin through the early American companies such as Benjamin Pike of New York and Chamberlin and Wightman of Boston right down to our present manufacturers and dealers.

As most of the data collected by Mr. Child have been obtained through personal conversation and correspondence with the direct descendants of the early laboratory supply pioneers, the book is truly authentic and of real value as a history of a young, vigorous and rapidly-growing American industry. The book is generously illustrated, containing many cuts of historically important apparatus and pictures of pioneers in the industry.

On the whole the book is fairly complete in its coverage. One is surprised, however, to note no mention of Caesar Tagliabue of the C. J. Tagliabue Mfg. Co., one of the originators of standardized American-made oil-testing equipment. Likewise, the present industrial importance of the fine work done by the Standardization Committee of the American Chemical Society, as well as that done by the many committees of the American Society for Testing Materials, would seem to warrant more emphasis on the part of the author.

In spite of these few shortcomings this book may well be considered a real contribution to the history of chemical education in America.—ARTHUR SCHRODER, *Chicago.*

Élasticité et Photoélasticimétrie. By HENRI LE BOITEUX and ROBERT BOUSSARD. Hermann & Cie, Paris, 1940. Paper, 6½ × 10 inches, 361 pages, 231 figures. Price 180 Francs.

The science of photoelasticity or the optical method of stress analysis has within the last ten years experienced a remarkable growth. New methods have been developed and new techniques perfected. The complete exploration of two-dimensional stress fields was radically simplified, making many of the older methods obsolete. This made it possible to solve important industrial problems. In addition, the scope of the photoelastic method has been extended from strictly two-dimensional problems to space or three-dimensional problems.

The growth of the science of photoelasticity and the increasing rôle which it began to play in the engineering world manifested itself first in a marked rise in the research literature and second in the number of serious books on the subject. Whereas prior to 1930 there was hardly a book on photoelasticity there are today at least a half a dozen such books in English, Russian, German and the latest in French.

To the best of this reviewer's knowledge the book by Messrs. Boiteux and Boussard is the first French book on Photoelasticity. This book consists of four parts and thirteen chapters. Part I is an introduction to the theory of elasticity with special empnasis on two-dimensional problems. Part II develops the electromagnetic theory of light and the necessary principles of crystal optics. Part III discusses the stress optic law, photoelastic equipment, construction of models, isoclinics and stress trajectories. In Part IV the authors take up the problem of the determination of separate principal stresses. Here we find a description of Mesnager's method leading to interferometers and lateral extensometers, Favre's complete optical method and Filon's graphical integration for the determination of principal stress along stress trajectories. The latter is illustrated with two numerical examples: one a bar in tension with a symmetrical bulge such as may be produced by some types of welding, the other a simple beam in central bending. The materials used for models are celluloid and a plastic which they refer to as Rhodoid which seems to resemble bakelite in sensitivity.

The general impressions of this reviewer are mixed in character. The theoretical aspects of elasticity are well treated and clearly presented. There are a good many line drawings which facilitate the reading. The treatment of optics follows the electromagnetic theory which is mathematically rather involved for most engineers. The theoretical chapters are, however, among the best in the book. But Photoelasticity is decidedly more than a theory. Its value to the engineer lies in its ability to provide powerful practical tools for quantitative stress determination. The engineer is therefore primarily interested in the progress in the technique, methods and the accumulated data already obtained. From this point of view the volume under consideration reflects more nearly the state of our science of 1930 than of today. The authors seem to have lost contact with most of the developments made in recent years. This is evidenced by their persistent adherence to colored stress patterns, which except for qualitative demonstration are now generally outmoded. The book contains eight colored stress patterns but not one single black and white fringe photograph. Instead we find a rather large number of free-hand sketches of isochromatic lines.

One is also impressed by the complete absence of any reference to American work since 1930 as well as by the absence of any photoelastic data on the vital subject of stress concentration. The book furnishes an adequate, although unnecessarily obstruse, treatment of the theory of photoelasticity but it does not give a true picture of the present state of the technique, methods and accomplishments which are at a much higher level, at least in this country, than that exemplified by this work.

—M. M. FROCHT, Ph.D., *Associate Professor of Mechanics, in charge of Photoelastic Laboratory, Carnegie Institute of Technology, Pittsburgh, Pa.*

A Primer of Time Study. By F. M. SHUMARD. McGraw-Hill Book Company, New York, 1940. Cloth, 6 × 9 inches, xii + 520 pages. Price $5.

The author exhibits the effects of a background in industry and illustrates every point by descriptions of time study situations within his experience. Although the book shows no sign of a knowledge of scientific applied psychology, the author does not hesitate to refer to "Psychologists", social scientists, character analysts, . . . with the dogmatic assertion, "Although results have occasionally been achieved of genuine interest to the realm of pure science, it is only fair to point out that such studies have not yet produced any factors of knowledge which are applicable to applied science as manifested in our industrial life."

Having thus disposed of the practical values of general psychology, he proceeds to list the character traits required for a good time study man each on the basis of a *percentage rating scale,* and with no con-

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deration for the fact that such terms as "Imagination," "Sense of Fairness," "Power of Sympathy," "Salesmanship," "Leadership," etc., represent intangibles, subject to immense overlap in definition, and having little statistically proven reliability. He furnishes no criterion for the statistical reliability of his ratings. Yet he says, "Time study may be properly termed a science."

He says, "The T.S.M. (time study man) should be restricted to extreme limits of error," but the only instrument of precision used in all of his timing operations is a stop watch graduated in hundredths of a minute! Perhaps his statement, "A good T.S.M. need not have a thorough mechanical ability to do his job accurately, although any experience he may have had on the task he is analyzing will be of benefit to him. The president of a successful automobile factory does not necessarily have to be a composite of the fastest and most skilled operators on every job in the organization," explains the fact that this book is conspicuous by the absence of any presentation of the principles of *modern* instrumentation in time study. This is a textbook of stopwatch methods, purely, written from anecdotal experiences of a practical time study man who shows no effects of a training in the statistical methods of personnel validation and reliability.

On the positive side of the evaluation of this book, there are several suggestive contributions. The intangibles behind time study data, long a sore problem in accurate standards, may be reduced by the use of rating scales. Without question, he has a method here which is worth trying. His bias against "pure science" is such that he will probably never acquiesce to the idea that the psychologist's classifications of rating scale errors are pertinent to his work. But the addition of rating scale techniques to time study data offers a suggestion for handling the *quality* factor in work output. His practice exercises are an excellent idea, particularly those which are objectively measurable, and therefore potentially a validating check on the time study man's judgment. Some of his practical conclusions do parallel the findings of general psychology, whether he knows it or not. He has verified the rather startling effect of piece-rate motivation on employee output and advises the green time study man to avoid being influenced by previous day-rate outputs. The *range of scores* in his rating scale is from 40 to 100. Since he tries to make the ratings proportional to output per unit of time, this means that fastest workers have a production-ratio to poorest workers of about 2½:1. This is in moderately good agreement with other findings on the individual differences of workers in the simpler skilled jobs. He makes no rating scale allowance for the fact that individual differences can be both greater and less, depending on the mental requirements of the occupation.

He presents practical forms for observation sheets, gives practice problems on the basic arithmetical calculations of time study data, deals with time study difficulties in peculiar and unusual occupations, and gives some consideration to the problem of wage-setting from time-study data. He leans toward a sympathetic attitude concerning laboring men's attitudes, as they conflict with traditional methods. He believes that it should be possible for a time study man to set time units or Credors so accurately that the frequent cutting of base scales should not be necessary, and this without starting with a rate which is "too tight." The "pure science" man will agree with him heartily that fatigue allowances and fatigue facts should be based on data warrant and not on somebody's speculative curve of functions, having no more basis of validity than some man's opinion. Perhaps this author might profit by a greater realization that general science is not as speculative as he thinks, and that general science research men will be fully appreciative of his fact-finding attitude.

—ADELBERT FORD, *Head Dep't of Psychology, Lehigh University, Bethlehem, Pa.*

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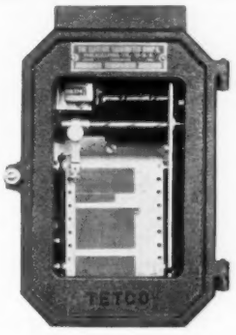

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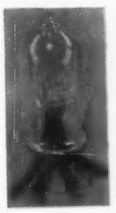

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